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## Machinability

Hans Kurt Toenshoff
Institute of Production Engineering and Machine Tools, Leibniz University Hannover, Garbsen, Germany

### Synonyms

Ability to be machined; Cut ability; Cutting property

### Definition

Machinability is the property of a material or a part to be machined, i.e., to remove material by cutting or abrasive processes, under given conditions (process inputs), while the process interactions and/or process outputs are evaluated under defined criteria.

### Theory and Application

From a system-oriented point of view, cutting processes can be described as black boxes with input variables, process interactions, and output variables (Fig. 1). In the process, the input variables are converted into output variables by process interactions. The input variables can be divided into system variables and manipulated or set variables. System variables describe process conditions which are either completely fixed or at least constant over a relatively long period of time. They depend on the machine tool (static and dynamic stiffness, thermal sensitivity), the workpiece (strength, shape of the raw part, chemical composition, structure), and the tool (material, shape, mechanical, and thermal properties).

The manipulated or set variables for each workpiece or job order are usually assessed and adjusted manually or using a program memory. They include the rotational speed or cutting speed, feed speed (depth of cut), and width of cut (infeed of the tool towards the workpiece). Furthermore, they can include the cutting fluid supply and the clamping force applied to fix the workpiece.

The process interactions like resultant forces, powers, temperatures in the chip formation zone, vibrations caused by the process, and acoustic emissions are only perceivable during the actual process. They can be used for monitoring or diagnosing purposes.

Process outputs are the effect variables. They can be measured at the workpiece (deviations in dimension, shape and position, microgeometry, physical influence on the surface zone), at the tool (wear), at the machine tool (temperature rise, wear), and in the cutting fluids (temperature rise, contamination, and chemical properties). They can be used to describe the effects of the process. From the process interactions and the process output, four main criteria are commonly deduced evaluating the **machinability** (see marked items in Fig. 1):


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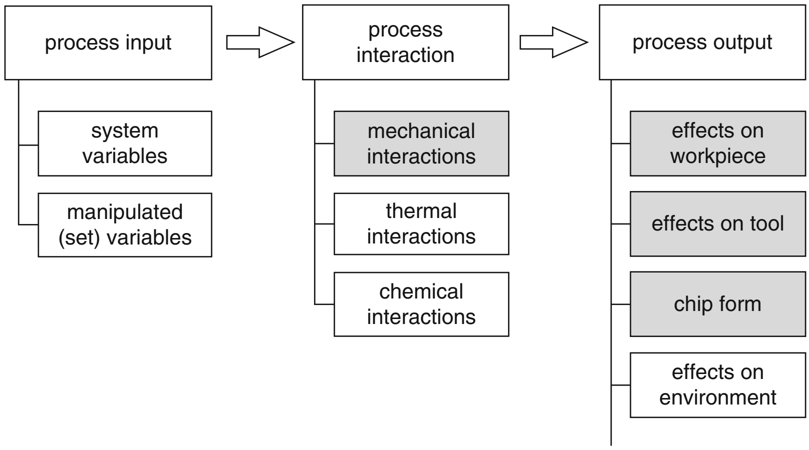



**Machinability, Fig. 1** The cutting process as a black box system

- Resultant force
- Tool wear
- Surface and properties of the workpiece
- Chip form

The *resultant forces* influence the design of the machine tool drives, the design of the machine tool frame, respectively, the deformation of the machine tool frame, the power requirement, the elastic deformation of the workpiece and the tool, and the requirements on the clamping systems for the workpiece and the tool. The *tool wear* has a crucial influence on the economic efficiency of the process. The deviation of the *surface properties* from the ideal target values (dimensions, shape, position, roughness, and physical properties of the external zone) determines the workpiece quality.

The *chip form* is important for the tool design (flutes or gullets for chip removal), for the design of the working space of the machine tool, and for an error-free process (process reliability).

These criteria have been set up, regardless that the ability to perform a machining task is always dependent on the given boundary conditions. The machinability is dependent particularly on the material of a part to be machined. Therefore the interdependence of the material properties and the machinability has to be regarded separately.

## Cross-References

▶ Cutting, Fundamentals
▶ Machinability of Aluminum and Magnesium Alloys
▶ Machinability of Carbon-Fiber-Reinforced and GLARE Materials
▶ Machinability of Carbon Steel
▶ Machinability of High-Alloyed Steel and Stainless Steel

## References

Klocke F (2011) Manufacturing processes. Springer, Heidelberg
Toenshoff HK, Denkena B (2011) Basics of cutting and abrasive processes. Springer, Heidelberg (in German)

# Machinability of Aluminum and Magnesium Alloys

Jens Köhler
ProWerk GmbH, Wedemark/Hannover, Germany

## Synonyms

Aluminum cast alloys; Aluminum wrought alloys; Chip formation; Cutting forces; Surface integrity

## Definition

Machinability is the quality of a solid material to be machined under given terms. It is evaluated by the output parameters of the machining process which are the influences on tool and workpiece and the quality of chips. These parameters are influenced by the mechanical, thermal, and chemical interactions during the machining process.

Light metal alloys based on aluminum and magnesium offer in general good machinability.

## Theory and Application

### Introduction

With a density of 1.7 g/cm$^3$ for magnesium and 2.7 g/cm$^3$ for aluminum, both materials are considered as light metals. That is why they are preferred construction materials for the automotive as well as aerospace industry where weight reduction is an important issue. The alloys of both metals are in general known for their excellent machinability.

### Process Interaction

The minor strength of magnesium and aluminum alloys leads to low cutting forces during the machining process. In comparison with steel of the same hardness, the cutting forces for aluminum are reduced to approximately 30%. Due to the relatively low cutting forces, it is possible to machine aluminum and magnesium alloys with high depth of cuts as well as high width of cut. Both magnesium and aluminum alloys have a good thermal conductivity. The heat which is generated due to friction between the workpiece and the tool dissipates through the metal away from the chip generation zone (de León 2010). In this zone the temperature is therefore reduced. Consequently, in general no cooling lubricants are needed to machine magnesium and aluminum alloys, and it is possible to apply high cutting speeds. However, in most application in aluminum machining, a coolant is used to increase the workpiece quality and to enable good chip transportation. A limiting factor regarding the cutting speed is given by the low melting point of both metals, which is 650 °C for magnesium and 660 °C for aluminum. If the process temperatures exceed this point, the metals ignite. It is therefore highly recommended to make sure that the arising temperatures are considerably lower.

At very low as well as at very high cutting speeds, chemical interactions between the workpiece and the tool can occur. For low cutting speeds, a buildup edge occurs due to adhesive effects and the material properties (Pekelharing 1974). For high cutting speeds, the temperature in the shear zone increases so that the aluminum in that zone becomes ductile. If in addition to that a suitable affinity between workpiece and tool material is given, the workpiece material reacts with the tool material and flank buildup appears, also known as deceptive chipping (Tomac et al. 1991). For the machining of aluminum alloys, the buildup edge is the dominant type of material buildup while for the machining of magnesium alloys flank buildup is dominating. An indication of flank buildup is the increase of process forces (Fig. 1).

Not only the process forces but also the temperatures rise with flank buildup. This is especially important when the process temperatures without buildup are already close to the ignition temperatures so that the arising flank buildup will cause the metal to ignite. Figure 2 shows simulated temperatures for external cylindrical turning on the magnesium alloy AZ91 with and without deceptive chipping.



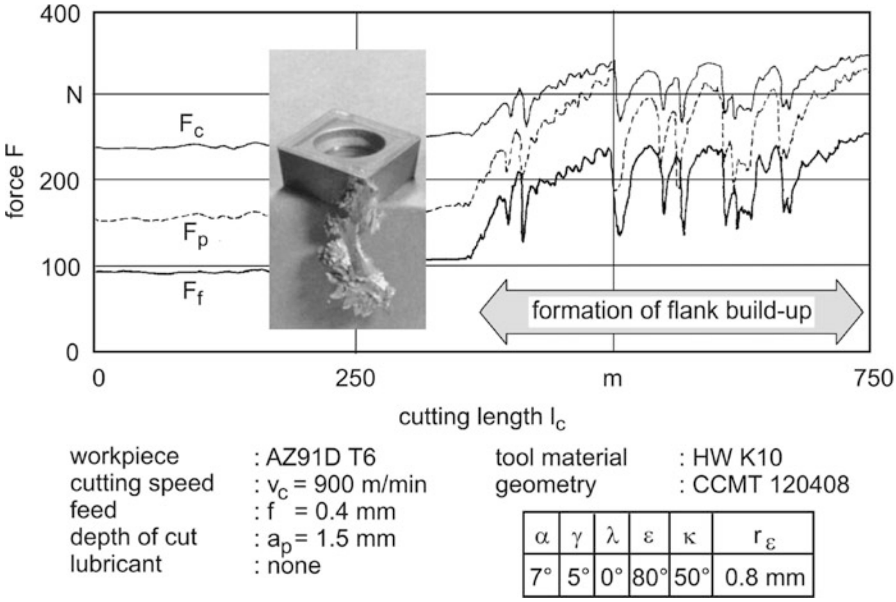
### Process Output

#### Tool Life

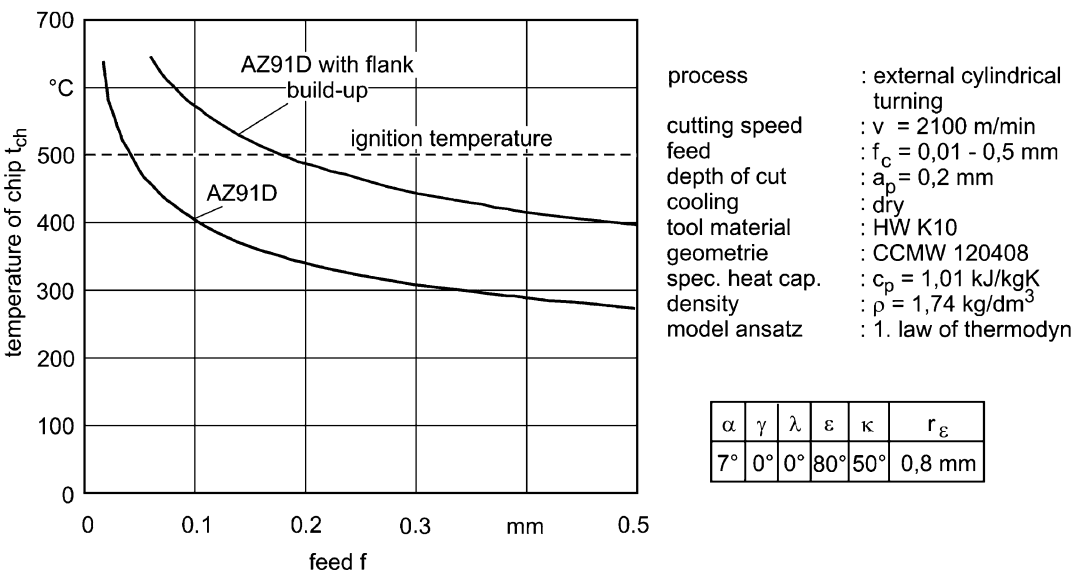
Common tool materials for machining aluminum and magnesium alloys are cemented carbide and polycrystalline diamond (PCD). Because of the strong affinity between aluminum and titanium, only tungsten-based cemented carbide tools are used for alloys with relevant aluminum contents.

For the machining of magnesium and most of the aluminum alloys, abrasive wear is limited. Only for AlSi-cast alloys, abrasive wear is a crucial factor. Especially for hypereutectic alloys with silicon content above 12%, tool wear is strongly increased compared to hypoeutectic alloys (Kammer 2003).

The predominant tool wear mechanism for machining magnesium and aluminum is adhesive wear. For the magnesium alloy AZ91, the influence of tool material on flank buildup has

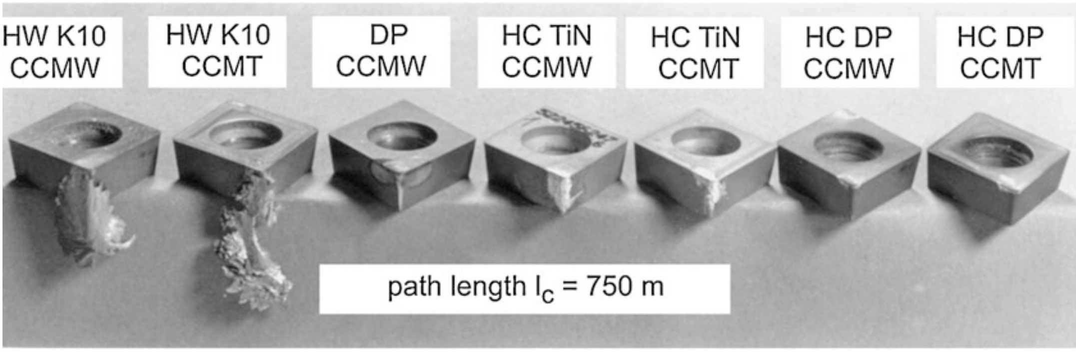



**Machinability of Aluminum and Magnesium Alloys, Fig. 1** Influence of flank buildup on the process forces (Toenshoff and Winkler 1997)




**Machinability of Aluminum and Magnesium Alloys, Fig. 2** Simulated temperature of the chips for external cylindrical turning of AZ91

been analyzed by Toenshoff and Winkler (1997). Figure 3 compares uncoated cemented carbide tuning tools (HW K10) with TiN (HC TiN) and diamond-coated (HC DP) ones and tools with a polycrystalline diamond insert (DP). The tools have been used for external cylindrical turning at $v_c$ = 900 m/min, f = 0.4 mm, and $a_p$ = 1.5 mm for a total cutting length of $l_c$ = 750 m. Except for the diamond-coated tools, material buildup can be found on




process : external turning
workpiece : AZ91D
cutting speed : $v_c$ = 900 m/min
feed rate : f = 0.4 mm
depth of cut : $a_p$ = 1.5 mm
cooling lubricant : none

tool material : HW K10, HC TiN HC DP, DP
geometry : CCMW 120408 CCMT 120408

| α | γ | λ | ε | κ | $r_ε$ |
|---|---|---|---|---|---|
| 7° | 0° | 5° | 0° | 80° | 50° | 0.8 mm |

**Machinability of Aluminum and Magnesium Alloys, Fig. 3** Flank buildup on turning tools after a cutting length of 750 m (Toenshoff and Winkler 1997)



the flank faces of all turning tools. The largest material adhesion exists on the uncoated tools.

### Surface Quality

The best surface qualities in machining aluminum alloys can be achieved by using diamond tools. Because of the low process forces, diamond tools with very sharp cutting edges are not prone to micro breakouts and allow clear-cuts which result in smooth surfaces (Kammer 2003).

In contrast to that, Denkena et al. showed that for milling of WE43, the resulting surface quality is better for uncoated cemented carbide tools than for diamond tools (Denkena et al. 2006) (Fig. 4).

For coated and uncoated cemented carbon tools, the limiting factor on surface quality is the material buildup. Buildup edges as well as flank buildup cause very rough surfaces.

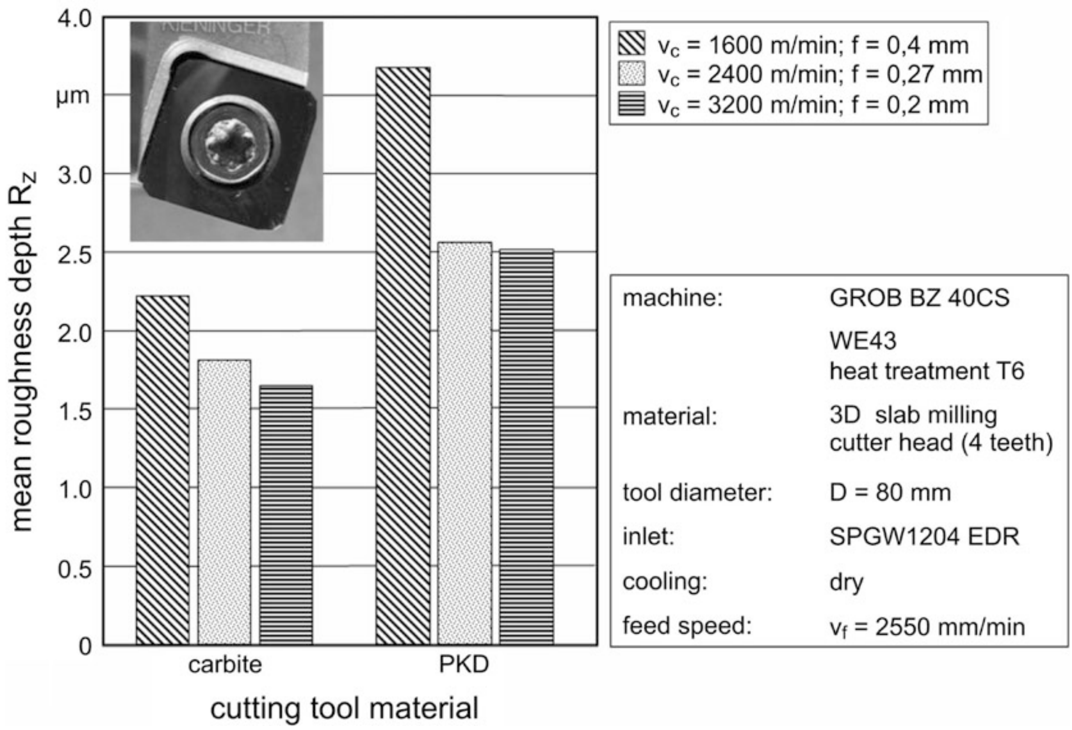
### Surface Integrity

The analysis of the subsurface shows that the machining of basically all magnesium and aluminum alloys results in compressive residual stresses. Merely the magnitude of the stress depends on the production process. There are compressive stresses found in the range of 0–30 MPa after turning MgCa0.8 at a cutting speed of $v_c$ = 100 m/min, while the measured stresses for face milling of MgCa0.8 with $v_c$ = 1200–2800 m/min are found in the range of 300–500 MPa (Denkena and Lucas 2007; Guo and Salahshoor 2010).

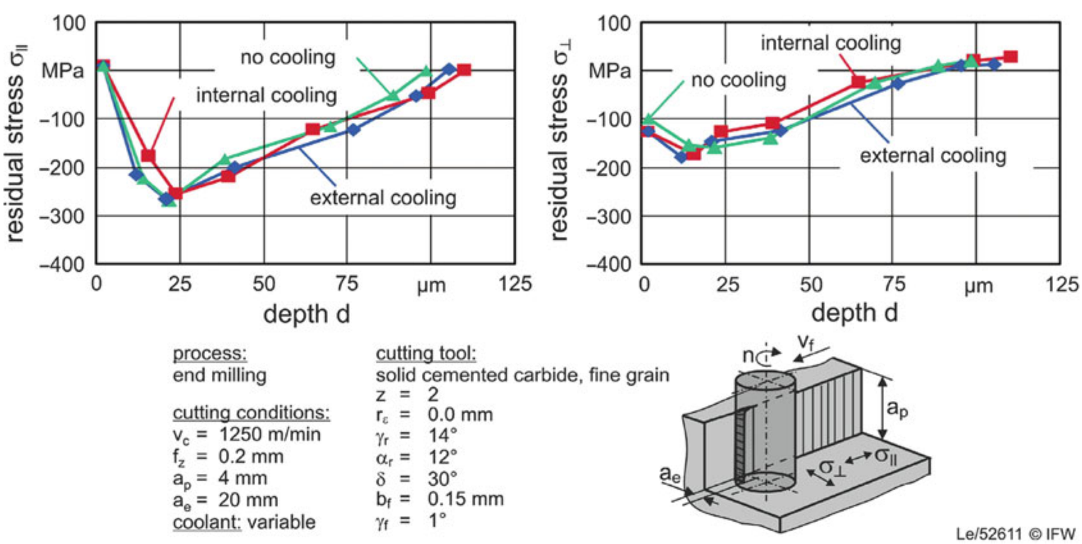
That there are no tensile stresses found corresponds with the findings of de Leon who studied the influence of face milling on the surface integrity of the aluminum wrought alloy Al7449. In his work he states that thermal effects – which are considered to be responsible for tensile residual stresses – have no significant influence on the generated residual stresses (de León 2010). Consequently, cooling strategies have no significant influence on residual stress formation (Fig. 5).

### Chips

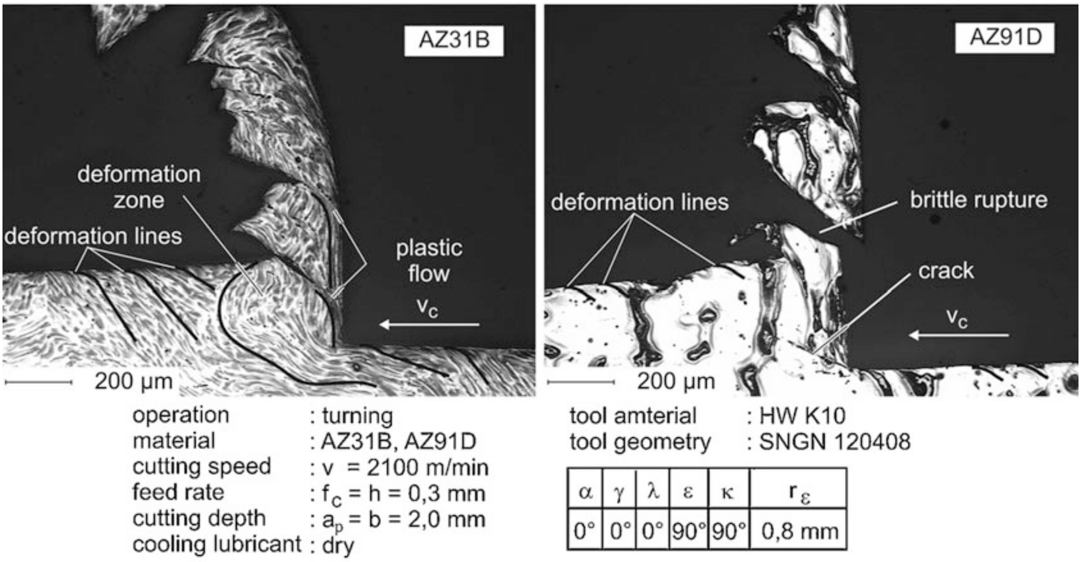
The chips resulting from machining magnesium alloy are mostly segmented. With increasing ductile yield, the plastically deformed material holds the segments together. Figure 6 shows the chip formation for AZ31 (7% ductile yield) and AZ91 (1% ductile yield) (Toenshoff et al. 2006).




**Machinability of Aluminum and Magnesium Alloys, Fig. 4** Surface roughness for milling WE43 with uncoated cemented carbide and polycrystalline diamond tools at variable cutting speed (Denkena et al. 2006)




**Machinability of Aluminum and Magnesium Alloys, Fig. 5** Influence of cooling on residual stress in the subsurface for face slab milling of Al7449 (de León 2010)




**Machinability of Aluminum and Magnesium Alloys, Fig. 6** Chip formation at AZ31 and AZ91 (Toenshoff et al. 2006)

For aluminum alloy the chip formation depends on the strength of the material. Softer grades of wrought alloy have ribbon and snarled chips, while for harder grades cylindrical helical chips are found (Kammer 2003).

## Summary

Aluminum and magnesium alloys offer a good machinability. Low cutting forces enable applying high cutting cross sections, and the good thermal conductivity allows dry machining. It has to be considered that the chips are liable to ignition if the temperatures during process rise to high. At low and at high cutting speeds, buildup edges and flank buildup arise. These effects can be avoided by using PKD-coated tools. Thermal effects have no significant influence on generated residual stresses in the subsurface of the workpiece. Consequently, no tensile stresses are induced by the machining process.

## Cross-References

▶ Cutting, Fundamentals
▶ Machinability

## References

de León L (2010) Residual stress and part distortion in milled aerospace aluminium, Berichte aus dem IFW [IFW-Reports], Band 01/2010, Doktorarbeit, PZH Produktionstechnisches Zentrum GmbH, Hannover

Denkena B, Lucas A (2007) Biocompatible magnesium alloys as absorbable implant materials – adjusted surface and subsurface properties by machining processes. Ann CIRP 56(1):113–116

Denkena B, Bach Fr-W, Weinert K, Alpers P, Bosse M, Hammer N (2006) Einfluss spangebender und spanloser Oberflächenbehandlung auf das Korrosionsverhalten und die mechanischen Eigenschaften von Magnesiumlegierungen [Influence of machining and non-cutting processes on corrosion behavior and mechanical properties of magnesium alloys], Tagungsband zum Congress Intelligente Leichtbau Systeme (ILS), 5–6 Sep 2006, Hannover (in German)

Guo YB, Salahshoor M (2010) Process mechanics and surface integrity by high-speed dry milling of biodegradable magnesium-calcium implant alloys. Ann CIRP 59(1):151–154

Kammer C (2003) Aluminium Taschenbuch – Bd. 3: Weiterverarbeitung und Anwendung [Aluminum pocketbook – Vol. 3: finishing and application], 16th edn. Aluminium, Düsseldorf (in German)

Pekelharing AJ (1974) Build-up edge (BUE): is the mechanism understand? Ann CIRP 23(2):207–212

Toenshoff HK, Winkler J (1997) The influence of tool coatings in machining of magnesium. Surf Coat Technol 94–95:610–616

Toenshoff HK, Denkena B, Winkler J, Podolsky C (2006) Machining – technology of magnesium and

magnesium alloys. In: Friedrich HE, Mördike BL (eds) Magnesium technology: metallurgy, design data, applications. Springer, Berlin, pp 398–430
Tomac N, Tønnessen K, Rasch FO (1991) Formation of flank build-up in cutting magnesium alloys. Ann CIRP 40(1):79–82

# Machinability of Carbon Steel

Dieter Lung
Cutting Technology, WZL, RWTH Aachen University, Aachen, Germany

## Synonyms

Cutting of carbon steel; Machinability of unalloyed steel

## Definition

### Materials

Unalloyed steels are colloquially often referred to as carbon steels. The “American Iron and Steel Institute (AISI)” defines carbon steel as follows: “Steel is considered to be carbon steel when no minimum content is required for chromium, cobalt, molybdenum, nickel, niobium, titanium, tungsten, vanadium or zirconium, or any other element to be added to obtain a desired alloying effect.” Regarding the maximum content of elements permitted in unalloyed and carbon steels, respectively, no consistent standard globally exists. According to DIN EN 10020 (DIN EN 10020 2000), the permitted limits of the main alloying elements for unalloyed steels are defined as follows: manganese <1.65%, silicon <0.60%, copper <0.40%, lead <0.40%, chromium <0.30%, cobalt <0.30%, nickel <0.30%, and tungsten <0.30%.

### Machinability

In general, machinability is defined in the term ‘Machinability’.

## Theory and Application

### Introduction

Depending on their alloy content, steel materials are divided into unalloyed steels, colloquially often referred to as carbon steels, low-alloyed steels (alloy content <5%), and high-alloyed steels (alloy content ≥5%). Within these materials, carbon steel is the most widely used kind of steel with applications in a huge range of products, e.g., car bodies, shafts, gears, or springs (see Fig. 1). Depending on their carbon content, carbon steels can be subdivided into low, medium, high, and ultrahigh carbon steels. Furthermore, unalloyed/carbon steels are in general divided into those steel materials that are not to be heat-treated (common construction steel) and those that are (grade and special steel). Steels referred to as common construction steels (e.g., S235JR) exhibit minimum values regarding their mechanical properties and are used in practice when no special requirements are made regarding their structure.

The machinability of carbon steel predominantly depends on the microstructure of the material which is determined by the carbon content, as well as the thermal history or heat treatment. Alloying and residual elements have only a minor influence on the machinability of carbon steel due to their low contents. Manganese, exhibiting the highest maximum amount of all alloying elements in carbon steels of up to 1.65%, may form manganese sulfides when small amounts of sulfur are also added. Thus, the machinability, especially of low carbon steel, is improved in terms of chip formation, surface quality, and resistance against built-up edge formation.

In the following, the main factors influencing the machinability of carbon steels are described (according to Klocke 2010). Moreover, recommendable tool materials and geometries, cutting fluids, and cutting parameters are specified.

### Crystalline Constituents of Carbon Steel

Main crystalline constituents in carbon steels are ferrite, cementite, perlite, and, depending on heat treatment, bainite and martensite. Below approximately 723 °C, austenite in carbon steels is

**Carbon Steel***
C < 2.06%, Mn < 1.65%, Si < 0.6%,
Cu < 0.4%, Pb < 0.4%, Cr < 0.3%

| | Low-carbon steel<br>C ≤ 0.3% | Medium-carbon steel<br>0.3% < C ≤ 0.55% | High-carbon steel<br>0.55% < C ≤ 1.0% | Ultrahigh-carbon steel<br>1.0% < C ≤ 2.06% |
|---|---|---|---|---|
| **Typical materials**** | S235JR, C15E, C26D, 17Mn4 | C35E, C40E, C45E | C60E, C70E, C85W | C125W, C130 |
| **Micro-structure** | Mainly ferrite, minor amounts of perlite | Nearly balanced amounts of ferrit and pearlite | Mainly perlite, minor amounts of ferrite or cementite | Perlite with secondary cementite |
| **Applications** | Automobile body panels, tin plate, wire products | Shafts, axles, gears, forgings, rails, railway wheels | Spring materials, high-strength wires, wood saws | Files, gouges, reamers, knives, punches |

* Limits of alloying elements acc. to DIN EN 10020 ** Notation acc. to DIN EN 10027-1

**Machinability of Carbon Steel, Fig. 1** Classification of carbon steels (according to Cardarelli 2000; DIN EN 10020)



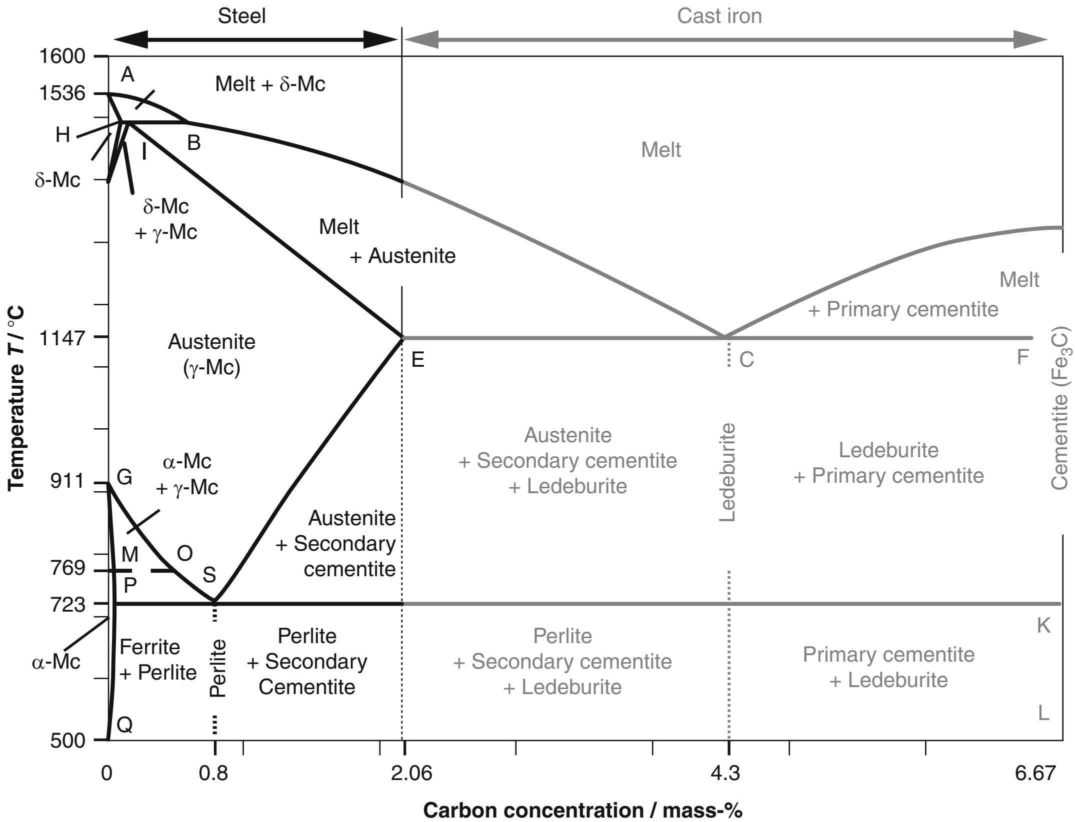
transformed into perlite and, according to the carbon content, ferrite or cementite. Thus, austenite is only present at room temperature in alloyed steels and not in carbon steels. The iron-carbon phase diagram shows the metallographic constitution for unalloyed carbon steels depending on the carbon content and the temperature, Fig. 2.

The important influence of the metallographic constitution of carbon steel on its machinability mainly results from the different mechanical properties of the respective crystalline constituents (Table 1).

***Ferrite*** (α-ferrite, cubic body-centered) has a maximal solubility of 0.02% for carbon and is characterized by a relatively low strength and hardness and by a high deformability.

The second basic structural constituent of carbon steel, ***cementite*** (iron carbide, $Fe_3C$), has completely different properties in contrast to ferrite. It is hard and brittle and thus cannot be cut. Cementite can occur either by itself or as a structural constituent of perlite or bainite, depending on carbon content and cooling speed.

***Perlite*** is an eutectoid phase mixture composed of approximately 87% ferrite and 13% cementite and occurs in iron materials with a carbon content between 0.02% and 6.67%. The eutectic point is at 723 °C and 0.83% carbon. At carbon contents below 2.06%, perlite appears as individual metallographic constituent, whereas above 2.06% carbon, it occurs in a phase mixture with cementite and ledeburite. In perlite, cementite




**Machinability of Carbon Steel, Fig. 2** Iron-carbon phase diagram (metastable system)

**Machinability of Carbon Steel, Table 1** Mechanical properties of metallographic constituents, according to Vieregge (1970)

| | Hardness/HV 10 | $R\ m$ /(N/mm$^2$) | $R\ p_{0.2}$/(N/mm$^2$) | Necking Z/% |
|---|---|---|---|---|
| Ferrite | 80–90 | 200–300 | 90–170 | 70–80 |
| Cementite | >1100 | – | – | – |
| Perlite | 210 | 700 | 300–500 | 48 |
| Austenite | 180 | 530–750 | 300–400 | 50 |
| Bainite | 300–600 | 800–1100 | – | – |
| Martensite | 900 | 1380–3000 | – | – |

predominantly appears in lamellar form. However, by means of a heat treatment (soft annealing), globular cementite can also be formed in perlite.

***Bainite*** is a crystalline constituent that can be formed during heat treatment of steel by isothermal transformation or continuous cooling in the temperature range between those of perlite and martensite. Here, iron diffusion is no longer possible, while carbon diffusion is already substantially hindered. Bainite consists of carbon-supersaturated ferrite, with carbon partially precipitated as carbides (e.g., $Fe_3C$) whose size (from rough to very fine) depends on the conversion temperature. Regarding its form, bainite is distinguished between acicular bainite (with continuous cooling and isothermal transformation) and granular bainite (only with continuous cooling). Acicular bainite can be further differentiated according to the transformation temperature in lower bainite (strong similarity to martensite) and upper bainite (strong similarity to perlite).

***Martensite*** is formed when steel with a carbon content above 0.2% is rapidly cooled from the austenite temperature range to a temperature below the martensite starting temperature. Due to the prompt cooling, the carbon dissolved in austenite is forced to remain dissolved in the mixed crystal. Martensite has a fine acicular, very hard, and brittle microstructure which causes increased abrasive wear and high mechanical and thermal stresses during machining.

## Influence of Carbon Content on Machinability

Carbon steel with a carbon content <0.8% precipitates ferrite when cooling from the austenite zone while the remaining austenite disintegrates into perlite. With rising carbon content, the amount of perlite increases until only perlite remains at C = 0.8%. Perlite and secondary cementite (precipitated from the austenite predominately at the grain boundaries) are formed in steels with a carbon content >0.8%. The machinability of carbon steel is significant depending on how much cementite is embedded in ferrite and in which form cementite is existent.

A schematic overview on the machinability of carbon steels with respect to tool wear and chip formation depending on carbon content is shown in Fig. 3. Thus, carbon steels with a carbon content of approximately 0.25% show the best machinability (Vieregge 1970; Cardarelli 2000).

The machinability of low carbon steels with a carbon content <0.25% is mainly characterized by the properties of the free ferrite. Because of the high deformability of the material and due to its strong tendency to adhere, material smearing on the tool and the formation of built-up edges and built-up edge fragments are induced, especially while machining with low cutting speeds. Hence, poor surface qualities and increased burr formation are often observed on the workpieces. In order to avoid the growth of built-up edges, cutting speeds should be kept above $v_c = 200$ m/min. The high deformability of ferrite moreover causes the tendency to form unfavorably long ribbon and snarled chips. However, in a positive perspective, it can be detected that tool wear and cutting temperature only increase slowly with a rising cutting speed. Regarding manufacturing processes, low carbon steels pose particular problems for grooving and parting off, as well as for boring, reaming, and thread cutting. Here, burr formation occurs to a greater extent, and the achievable surface qualities are poor, caused by

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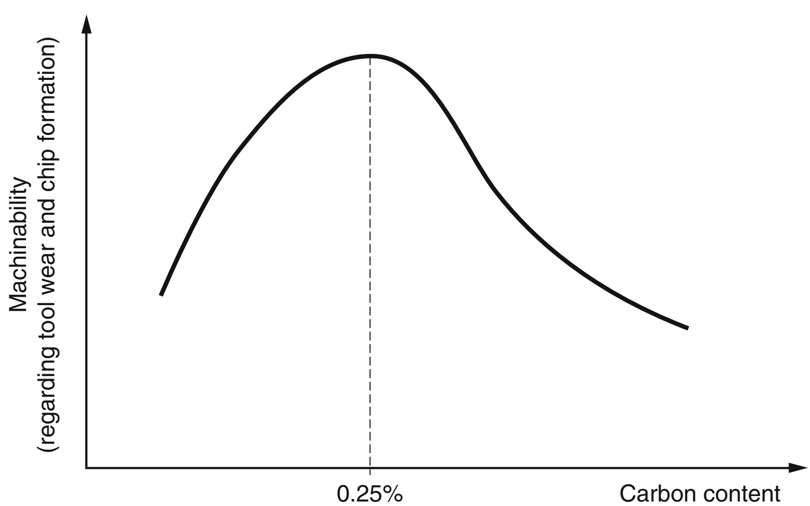


**Machinability of Carbon Steel, Fig. 3** Schematic correlation between machinability of carbon steels and carbon content, according to Vieregge (1970) the material's high deformability and relatively low cutting speeds.

With rising carbon content (0.25–0.4%), the amount of perlite in the structure of carbon steels increases. Thus, the influence of the properties of this metallographic constituent on the machinability gets stronger. The strength of the structure increases and its deformability is reduced. Hence, on the one hand, due to the lower deformability and greater hardness of perlite in comparison to ferrite, significant abrasive wear, high resultant forces, and higher temperatures in the tool contact zones are caused during machining. Positive effects of perlite on the machinability, on the other hand, are more favorable chip formation as well as reduction of adhesion tendency, surface roughness, formation of built-up edges, and burr formation. By means of a prior cold-forming process, the machinability of carbon steel with a carbon content between 0.25% and 0.4% can be affected in a positive way, particularly with respect to chip formation. This is important to the extent that these materials are often deformed by cold extrusion and then finished by cutting.

A further increase of the carbon content (0.4–0.8%) leads to a further reduction of ferrite with a corresponding perlite increase until only perlite remains at 0.83% carbon. Due to higher strengths, high rake face temperatures are already generated at low cutting speeds. Simultaneously, the increasing mechanical load on the rake face causes higher cutting forces and tool wear, especially in the form of crater wear. Hence, an early damage of the tool is likely even at low cutting speeds (Vieregge 1970). Carbon steels with a carbon content of 0.4–0.8% are in general regarded as having good machinability only concerning surface quality and chip form.

After slow air cooling, the structure of supereutectoid heat-treated steels ($C > 0.8\%$) consists of secondary cementite and perlite. Shells of free cementite are formed around the perlite grains, leading to very strong abrasive wear during machining as consequence of cementite's high hardness and brittleness (Schumann and Oettel 2004). Moreover, the arising high pressures and temperatures cause an extra stress for the cutting edge, leading to strong crater and flank wear even at relatively low cutting speeds.

## Heat Treatment for Improving Machinability

Heat treatments can influence the microstructure of steel with respect to quantity, form, and configuration of their constituents. In this way, mechanical properties and thus machinability can be customized to the given requirements.

Carbon steels with a carbon content $<0.2\%$ can be heat-treated to a certain ferrite/perlite structure or to a certain strength in order to preliminary improve their surface quality after cutting. The machinability of carbon steels with a carbon content between 0.3% and 0.4% can be enhanced by means of coarse-grain annealing in order to produce a coarse-grain structure with a ferrite network in which either perlite or bainite is enclosed (Schumann and Oettel 2004). Tool wear is relatively low when machining such a structure, and generally favorable chips are formed while achieving high surface qualities. Carbon steels exhibiting a carbon content above 0.35% can be normalized in order to achieve improved machinability. Through normalizing, a nearly even, fine-grain structure is achieved whose machinability is, depending on the carbon content, determined by the predominant structural constituent. A possibility to enhance the machinability of carbon steels with carbon contents $>0.4\%$ is soft annealing. This heat treatment is applied in order to reduce the high hardness and low deformability of structures with lamellar perlite or lamellar perlite and cementite. The goal is to achieve a perlite structure which is as granular as possible consisting of ferrite with globular cementite. The machinability of such a structure changes in the way that tool wear is decreased, whereas chip formation deteriorates to the extent that ferrite predominates in the microstructure.

## Tool Materials and Geometries

For machining carbon steels, cemented carbide tools belonging to application group P (according to DIN ISO 513) exhibit the largest area of application. Hereby, the tool materials have to exhibit a higher wear resistance with increasing carbon content. Most common cemented carbide tools used for cutting carbon steel are based on tungsten carbide. In order to withstand the increased thermal stress caused at high cutting speeds, especially during finishing processes, tools made of tungsten carbide mixed with high amounts of titanium carbide, as well as carbide tools based on titanium boron nitride ("cermets"), may be favorable (Childs et al. 2000; Klocke 2010). In order to improve the cutting performance, especially with respect to cutting forces and tool wear, special coatings have been introduced in the past decades. The most common coatings applied for machining carbon steels are made of TiC, TiCN, TiN, TiAlN, TiAlCN, and $Al_2O_3$, as well as their combination in multilayer coatings (Chang and Fuh 1995; Tuffy et al. 2004; Klocke 2010). Besides carbide tools, tools made of high-speed steels (HSSs) may be reasonable with respect to cost-efficiency when drilling, milling, broaching, sawing, or threading low carbon steel and, to some extent, medium carbon steel.

Besides the tool material, tool macrogeometry and microgeometry like rake and clearance angle, corner radius, cutting edge radius, etc. have a huge influence on the cutting result. For cutting low carbon steel (C $<$ 0.3%), specific chip breaking geometries are required for improving chip forming (Fang 1998). Only tools with the greatest possible positive tool orthogonal rake angle (e.g., turning: $\gamma_o > 6°$) should be used due to ferrite's low strength (Schönherr 2002; Klocke 2010). For medium carbon steel, a positive orthogonal tool rake angle should be applied as well (Klocke 2010). For cutting steels with higher carbon contents, especially with more than 0.8% carbon, the cutting edge needs to be designed stable, and for turning, the tools should have a positive orthogonal rake angle $\gamma_o$ up to 6° and slightly negative tilt angles $\lambda_s$ up to $-4°$ (Klocke 2010).

### Cutting Fluids

Cutting fluids are generally applied when machining carbon steel in order to provide sufficient cooling and lubrication in the cutting zone and to support chip evacuation. For low carbon steel, oils may be used as cutting fluids in order to reduce the adhesion tendency and to improve the surface quality. Here, the oil's lubrication properties are more important than its cooling effect (Klocke 2010). Flood cooling with emulsion as cutting fluid is widely used for machining carbon steels with higher carbon contents due to increased material's strength and higher temperatures generated in the cutting zone compared to low carbon steel. The application of minimum quantity lubrication (MQL) and dry machining with the aim of reducing costs for fluid purchase, disposal, and recycling is generally possible for cutting low and medium carbon steel. However, their application is only reasonable after carefully analyzing the machining task individually and adapting the manufacturing process, e.g., in terms of tool material and cutting parameters. For processes that do not allow the use of MQL or dry machining, vegetable-based cutting fluids might be an advantageous alternative compared to mineral oil-based fluids due to a higher biodegradability and lower environmental impact, as well as high machining performance. Mineral oils, however, are still significantly more widely used in industry due to their lower procurement costs. As alternative to mineral oil-based and vegetable-based cutting fluids, cryogenic cooling using carbon dioxide snow ($CO_2$) or liquid nitrogen ($LN_2$) may be applied in order to improve chip breakage and tool life (Hong et al. 1999; Stanford et al. 2009). However, this cooling strategy is still rarely used in industry due to open research questions regarding optimal $CO_2$, respectively, $LN_2$ supplying method, tool machine adaption, cost-effectiveness, and safety aspects.

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## Cross-References

▶ Coated Tools
▶ Cutting Fluid
▶ Cutting, Fundamentals
▶ Machinability of High-Alloyed Steel and Stainless Steel
▶ Wear Mechanisms

## References

Cardarelli F (2000) Materials handbook – a concise desktop reference. Springer, London

Chang C-S, Fuh K-H (1995) A study of cutting performance in turning plain carbon steel using TiN-coated, TiCN-coated, and uncoated cemented carbide tools with chamfered main cutting edge. Mater Manuf Process 10(3):453–472

Childs THC, Maekawa K, Obikawa T, Yamane Y (2000) Metal machining – theory and applications. Arnold, London

DIN EN 10020: 2000-07 (2000) Begriffsbestimmungen für die Einteilung der Stähle [Definition and classification of grades of steel]. Beuth, Berlin. (in German and English)
Fang N (1998) Influence of the geometrical parameters of the chip groove on chip breaking performance using new-style chip formers. J Mater Process Technol 74(1–3):268–275
Hong SY, Ding Y, Ekkens RG (1999) Improving low carbon steel chip breakability by cryogenic chip cooling. Int J Mach Tools Manuf 39(7):1065–1085
Klocke F (2010) Manufacturing processes 1 – cutting. Springer, Heidelberg
Schönherr H (2002) Spanende Fertigung [Cutting manufacturing]. Oldenbourg, Munich. (in German)
Schumann H, Oettel H (2004) Metallographie [Metallography], 14th edn. Wiley-VCH, Weinheim. (in German)
Stanford M, Lister PM, Morgan C, Kibble KA (2009) Investigation into the use of gaseous and liquid nitrogen as a cutting fluid when turning BS 970-80A15 (En32b) plain carbon steel using WC-Co uncoated tooling. J Mater Process Technol 209(2):961–972
Tuffy K, Byrne G, Dowling D (2004) Determination of the optimum TiN coating thickness on WC inserts for machining carbon steels. J Mater Process Technol 155–156:1861–1866
Vieregge G (1970) Zerspanung der Eisenwerkstoffe [Cutting of ferrous materials], 2nd edn. Stahleisen, Düsseldorf. (in German)

# Machinability of Carbon-Fiber-Reinforced and GLARE Materials

Ekkard Brinksmeier
University of Bremen, Leibniz-IWT, Bremen, Germany

## Synonyms

Cutting of fiber-reinforced plastics; Machining of CFRP/GFRP and composite materials

## Definition

### Materials

Carbon-fiber-reinforced plastic (CFRP) is a multiphase material consistent of the carbon fibers which are embedded into the polymeric matrix material. The third phase of the material is the interface which describes the zone between the fibers and the matrix material. CFRP is known by its excellent mechanical properties and the anisotropic material behavior.

GLARE (glass-fiber-reinforced aluminum) is a composite material consisting of thin aluminum and glass-fiber-reinforced plastic (GFRP) layers.

### Machinability

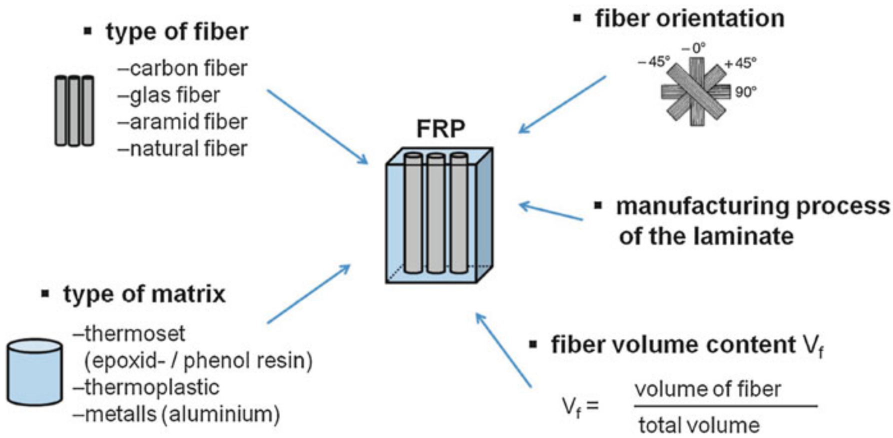
The machining process is used to separate the material, e.g., to generate a certain shape or geometry of the workpiece and to improve the surface quality. The machining of CFRP or composites is often difficult because of the inhomogeneous and anisotropic material properties.

## Theory and Application

### Introduction

Because of their excellent weight-specific properties, fiber-reinforced plastics belong to the high-performance materials in the field of lightweight design. The high specific strength and stiffness as well as the possibility to design material properties individually make them particularly interesting for structural components in the aircraft and space industry. They are often combined with aluminum and/or titanium alloyed sheets to take advantage of both material properties. These classes of materials are usually fitted to multilayered composites like GLARE (glass-fiber-reinforced aluminum). Composite materials are increasingly used in the sector of automotive, medical, and general engineering where they allow new opportunities regarding construction and design of the products (Brinksmeier et al. 2011; Chang 2006).

Components made of FRP and/or composite materials are usually manufactured near net shape; however, they have to be remachined to produce boreholes or notches in the workpiece and to improve the quality of contact or functional surfaces. Remachining is mostly done by milling, drilling, or grinding. The machining characteristics of FRP are fundamentally different compared to those of metallic alloys and the cutting mechanism is relatively unknown yet (Teti 2002; Schulze et al.




**Machinability of Carbon-Fiber-Reinforced and GLARE Materials, Fig. 1** Influencing factors to the mechanical properties of FRPs

2011; Davim and Reis 2005). The machinability is mainly influenced by the mechanical properties of the FRP which is determined by the type of fiber, the matrix material, the fiber volume content, the fiber orientation, and the manufacturing process. This large range of influencing factors makes it difficult to find relations with general validity. Due to the inhomogeneous and anisotropic material properties, machining of FRP comes along with certain difficulties like fiber pullout, delamination, and combustion of matrix material which leads to a degradation of the surface quality.

## Material Structure and Properties

### Fiber-Reinforced Plastics (FRPs)

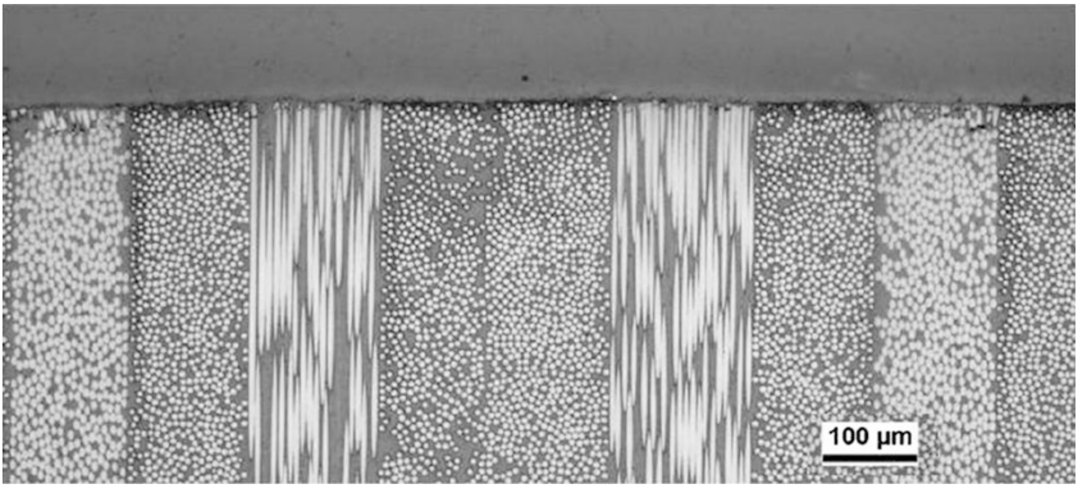
FRPs are consisting of the fibers (disperse phase) which are enclosed by the surrounding matrix system (continuous phase). The fibers are characterized by excellent mechanical properties like high tensile strength and modulus. However, they are showing a limp behavior comparable to a rope. Therefore, they are able to absorb high tensile loads whereas a compressive load causes diversion due to fiber bending. To manufacture a workpiece with a certain geometry, it is necessary to stabilize and fix the fibers. This purpose is taken over by the matrix system. Its function is to keep the limp fibers in position, absorbing compressive loads, transmitting forces between the fibers, and protecting the fibers from mechanical damage.

The mechanical properties of FRPs are influenced by the characteristic nature of its components, as shown in Fig. 1.

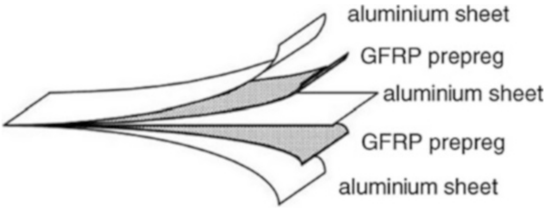
The structure and orientation of the reinforcing fibers in the matrix system are essential for the mechanical properties of the workpiece. The choice of a particular architecture is dependent on multiple factors like drapeability of the fabric, geometry/shape of the workpiece, mechanical requirements, and the manufacturing process. Components made of unidirectional layers (laminates) are showing the best mechanical properties since the fibers are completely stretched (no undulation). Usually the single layers of a laminate are showing different fiber orientations. This causes anisotropic material behavior in the planar direction. The structure of a multiaxial layered laminate is shown in Fig. 2.

### GLARE (Glass-Fiber-Reinforced Aluminum)

GLARE is a composite material which consists of thin aluminum and glass-fiber-reinforced plastic layers (see Fig. 3). Compared to pure aluminum alloys, GLARE offers various advantages like an improved tensile strength, low specific weight, a better fire, and impact behavior as well as a reduced fracture propagation. Furthermore, components made of GLARE can be designed according to a certain load condition by optimizing the fiber orientation of the glass fibers. GLARE is mainly used in the upper fuselage sections of modern aircrafts.




**Machinability of Carbon-Fiber-Reinforced and GLARE Materials, Fig. 2** Microsection of CFRP




**Machinability of Carbon-Fiber-Reinforced and GLARE Materials, Fig. 3** GLARE (glass-fiber-reinforced aluminum)

## FRP/Ti Composite

FRP/Ti composites belong to the most popular hybrid composite stacks. Typical configurations like CFRP/Ti6Al4V and GFRP/Ti6Al4V are widely used in aerospace industry and offer great advantages, like an outstanding strength-to-weight ratio and corrosion/erosion resistance, compared to standard composite and single metal materials.

## Cutting Materials for Machining of CFRP

Because of the brittle nature and high hardness of carbon fibers, they are showing a very abrasive behavior in the machining process. Dependent on the cutting material, this often results in substantial tool wear even after short cutting lengths. When cutting FRPs, the tool wear is mostly characterized by a rounding of the cutting edge as a consequence of the abrasive action of the hard fibers grinding at the tool flank. This is often associated with a decreasing surface quality.

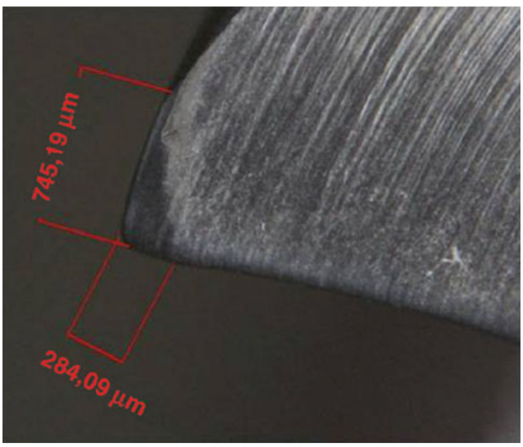
Figure 4 is showing the cutting edge of a fine-grained tungsten carbide tool after drilling CFRP. The rounded cutting edge is clearly visible. At the same time, the tool is not showing any other signs of wear-like adhesion or chipping. This indicates that abrasion is the predominant wear mechanism for machining of carbon-fiber-reinforced plastics. As a consequence, cutting materials with high hardness and wear resistance are preferable for the machining process.

Carbon fibers are showing the highest degree of abrasiveness compared to all other types of reinforcing fibers. Satisfactory results concerning tool life and surface quality were only achieved by highly wear-resistant cutting materials like polycrystalline diamond or diamond-coated solid carbide. Although CBN is also suitable for cutting of CFRP at the same price, there are no advantages compared to PCD tools. Hence, from an economical point of view, there is no reason for the use of CBN (Ferreira et al. 1999; Teti 2002).

Ceramic cutting materials were found to be insufficient for machining of CFRP. They offer high temperature and wear resistance but are showing a low heat conductivity which again leads to high local temperatures in the cutting zone. This might cause damage especially to the matrix material of the CFRP (Teti 2002).

## Cutting Mechanisms in Machining FRP, GLARE and FRP/Ti Composite

Investigations in machining of CFRP and composite materials are relatively rare compared to those of metallic alloys. However, it is agreed that the cutting mechanism of FRPs is fundamentally different from those of metallic alloys. The huge variety of combination possibilities regarding the fiber and matrix type claims for a comprehensive research in that field. The knowledge about the cutting mechanism is important for the process comprehension and, e.g., prediction of cutting forces or machining-induced damages in the workpiece (Bhatnagar et al. 1995; Ferreira et al. 1999; Chang 2006).




**Machinability of Carbon-Fiber-Reinforced and GLARE Materials, Fig. 4** Cutting edge rounding of a tungsten carbide tool after drilling of CFRP

Previous investigations reveal that the material separation in machining of CFRP is primarily initiated due to a brittle fracture. Plastic deformations which are crucial for the material separation of metals are almost not occurring. Koplev (1983) and Kaneeda (1989) claim that the type of the reinforcing fiber and the cutting tool geometry is crucial for the cutting mechanism. Klocke et al. (1999) has shown that the fiber orientation is influencing the cutting mechanism. The microsections in Fig. 5 are showing the surface area of unidirectional CFRP milled in different fiber orientations.

Visible damages can be found for specimens with a fiber orientation of 90° and −45°, while the surface for 0° and +45° appears to be very consistent and nearly free of cracks or other damages. Specimens with 90° fiber orientation are showing cracks extending frequently from the milled surface at an angle of 18° into the material at intervals of about 200 µm. These cracks are caused by the brittle material behavior of the CFRP. The worst results were found at a fiber orientation of −45°. The micrograph is showing a large crack beneath the surface as well as recurring cracks with a length of about 300 µm in direction of the fibers. This behavior is well known from other literature (Chang 2006). During the cutting process, the fibers are bent in the direction of the free surface. This causes a high tensile load perpendicular to the fiber direction. In this direction, the tensile strength of the unidirectional CFRP is very low (matrix properties are dominating) which causes large cracks parallel to the fiber orientation. At a

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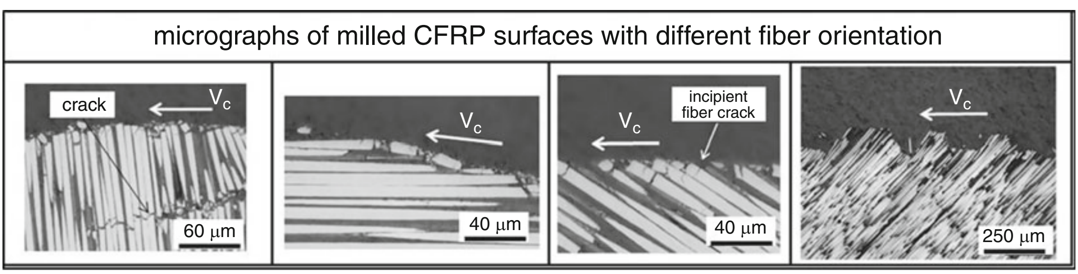
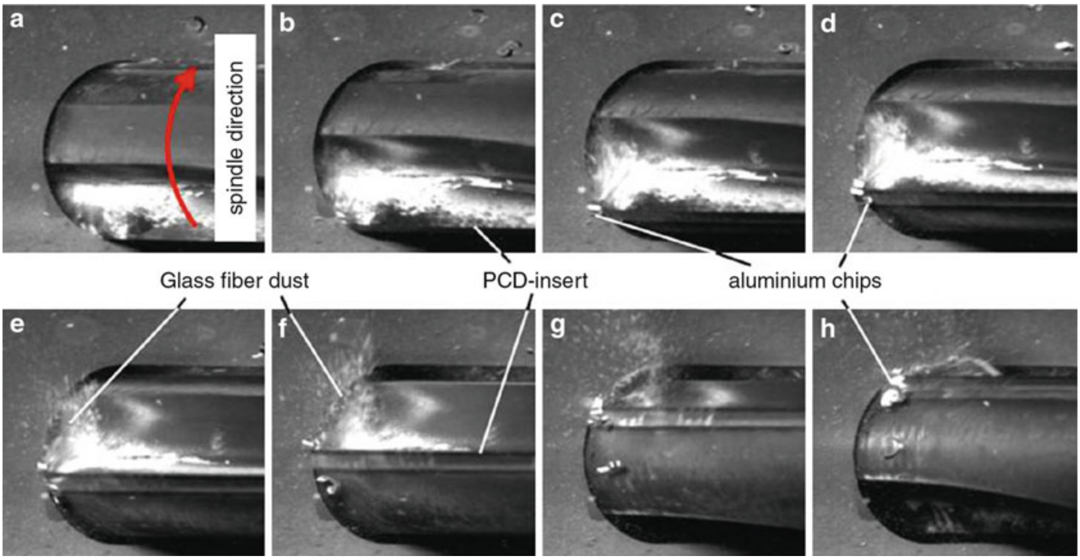
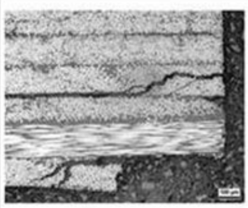
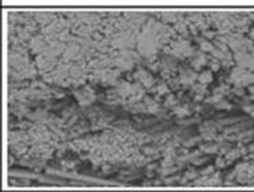



**Machinability of Carbon-Fiber-Reinforced and GLARE Materials, Fig. 5** Microsections of unidirectional CFRP specimens in different fiber orientations (Klocke et al. 1999)




**Machinability of Carbon-Fiber-Reinforced and GLARE Materials, Fig. 6** Slow-motion video pictures of a milling process of GLARE

| | | |
|---|---|---|
| **Delamination**<br>caused by tensile stresses perpendicular to the layer plain and shear stresses in longitudinal direction of the layer plain respectively |  | • reduce feedforce<br>• reduce feed rate<br>• try cutting tool with sharper cutting edge<br>• use alternative machining process |
| **Outbreaks mostly on the exit side)**<br>caused by tensile stresses perpendicular to the layer plain |  | • try cutting tool with sharper cutting edge<br>• use alternative machining process<br>• use glasply at exit side<br>• use crescent-shaped cutting edges |
| **Thermal damage of the matrix material**<br>caused by frictional heat |  | • reduce cutting speed<br>• use cutting material with higher heat conductivity<br>• use cutting material with lower friction coefficient |

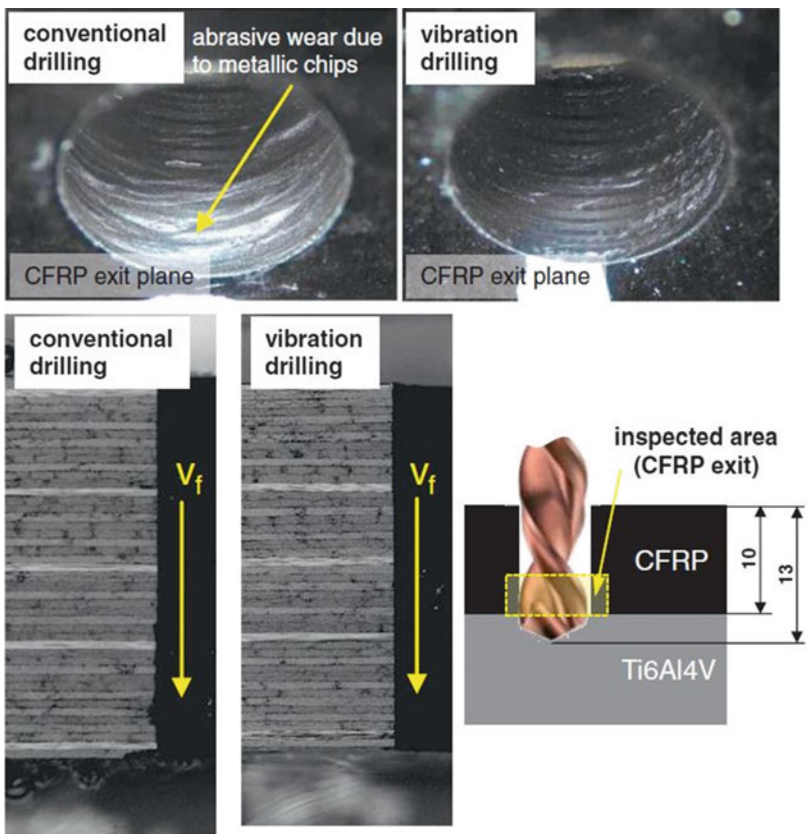
**Machinability of Carbon-Fiber-Reinforced and GLARE Materials, Fig. 7** Typical damages caused by machining of FRPs certain bending, the fibers are breaking beneath the surface and induce a crack parallel to the surface. By contrast for a fiber orientation of +45°, the tensile load is applied nearly in fiber direction where the tensile strength is maximal. This also causes very high cutting forces compared to a fiber orientation of −45°.

The slow-motion video pictures in Fig. 6 are showing half a turn of the cutting tool for a milling process of GLARE. From the chip evolution, it is clearly visible that each material of the composite shows its own characteristic behavior. In the aluminum layer, a continuous chip is formed during the cutting process while the GFRP layer is separated into small dustlike particles. The generation of dust indicates that the material is separated locally, directly at the cutting edge. A chip formation is not taking place. The velocity of the GFRP dust is higher than the cutting speed of the tool, which indicates that kinetic energy must be released due to the separation process.

In FRP/Ti composites the thickness of individual layers is significantly higher which lead to an increased variation of process values such as process forces during the machining process. Especially drilling operations in these material stacks are challenging tasks due to the considerably different properties of FRP and titanium alloys. The tools have to be designed to resist abrasive wear induced by hard carbon fibers and adhesions induced by the titanium layer. Previous investigations have shown that carbide tools with an AlCrN coating enable promising results (Pecat and Brinksmeier 2014b).

### Damage in FRPs

Machining of FRPs is often difficult due to the anisotropic and inhomogeneous material properties. Damages at the machined surface are often occurring. Figure 7 is showing the most common types of damages: delamination, fiber outbreaks, and thermal damage of the matrix material.




**Machinability of Carbon-Fiber-Reinforced and GLARE Materials, Fig. 8** Damages of the CFRP-layer by metallic chips for conventional drilling (Pecat and Brinksmeier 2014a)

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Delamination and fiber outbreaks are mostly occurring close to free surfaces where the reinforcing effect of the surrounding material decreases. This is especially critical at the exit side of boreholes. Ultrasonic inspection, thermography, or visual inspection is used for the damage detection. Thermal damage of the matrix material is mostly caused by high cutting speeds at poor cutting conditions. The identification of thermal damages is difficult because there is no acknowledged method of analysis yet.

In drilling operations of FRP/Ti composite a major problem is the mechanical friction of hot titanium chips at the borehole surface, leading to damages in the FRP layer. To minimize this damage mechanism it is advisable to use low frequency vibration assisted drilling (LFVAD) with an axial tool movement, superimposed by a sinusoidal oscillation. This allows an interrupted cut, small chip segments and, as a consequence, a significantly improved chip extraction (Fig. 8). Another advantage is the cutting temperature which can be reduced by more than 40%.

## Cross-References

- ▶ Burr
- ▶ Coated Tools
- ▶ Composite Materials
- ▶ Cutting, Fundamentals
- ▶ Machinability
- ▶ Wear Mechanisms

## References


Bhatnagar N, Ramakrishnan N, Naik N, Komanduri R (1995) On the machining of fiber reinforced plastic (FRP) composite laminates. Int J Mach Tools Manuf 35(5):701–716

Brinksmeier E, Fangmann S, Rentsch R (2011) Drilling of composites and resulting surface integrity. CIRP Ann Manuf Technol 60(1):57–60

Chang C-S (2006) Turning of glass-fiber reinforced plastics materials with chamfered main cutting edge carbide tools. J Mater Process Technol 180(1–3):117–129

Davim JP, Reis P (2005) Damage and dimensional precision on milling carbon fiber-reinforced plastics using design experiments. J Mater Proc Technol 160(2): 160–167

Ferreira JR, Coppini NL, Miranda GWA (1999) Machining optimisation in carbon fibre reinforced composite materials. J Mater Process Technol 92–93:135–140

Kaneeda T (1989) CFRP cutting mechanism. In: Proceeding of the 16th North American manufacturing research conference of the SME 15/3, Champaign, pp 216–221

Klocke F, König W, Rummenhöller S, Würtz C (1999) Milling of advanced composites, Chapter 8. In: Jahanmir S, Ramulu M, Koshy P (eds) Machining of ceramics and composites. Marcel Dekker, New York, pp 249–265

Koplev A, Lystrup A, Vorm T (1983) The cutting process, chips and cutting forces in machining CFRP. Composites 14(4):371–376

Pecat O, Brinksmeier E (2014a) Low damage drilling of CFRP/titanium compound materials for fastening. Procedia CIRP 13:1–7

Pecat O, Brinksmeier E (2014b) Tool wear analyses in low frequency vibration assisted drilling of CFRP/Ti6Al4V stack material. Procedia CIRP 14:142–147

Schulze V, Becke C, Pabst R (2011) Specific machining forces and resultant force vectors for machining of reinforced plastics. CIRP Ann Manuf Technol 60(1):69–72

Teti R (2002) Machining of composite materials. CIRP Ann Manuf Technol 51(2):611–634


# Machinability of High-Alloyed Steel and Stainless Steel


Dieter Lung
Cutting Technology, WZL, RWTH Aachen University, Aachen, Germany


## Synonyms

Cutting of high-alloyed steel and stainless steel; Machinability of non-rusting steel

## Definition

### Materials

Steel with alloy contents of ≥5% is referred to as high-alloyed steel.

Stainless steel contains at least 10.5% chromium and a maximum of 1.2% carbon and is therefore as per definition high alloyed. Based on their microstructure, stainless steels can be subdivided into ferritic, martensitic, ferritic-austenitic, and austenitic steels. According to their usage properties, stainless steels can be categorized into corrosion-resistant steels, heat-resistant steels, and high-temperature steels (Klocke 2010).

### Machinability

In general, machinability is defined at Machinability.

## Theory and Application

### Introduction

High-alloyed steels are distinguished from carbon steels and low-alloyed steels by their improved mechanical and thermal properties, which are adapted to their respective area of industrial application. For example, the alloying condition of high-speed steel is designed to withstand failure when cutting softer materials. Due to their high strength and ductility, excellent corrosion resistance, and thermal stability, stainless steels are often chosen for components in the chemical, marine, and food processing industry.

However, these favorable properties also result in a challenging machinability, which is reflected by high tool wear rates, unfavorable chip geometries, and rough surface qualities. In order to design stable cutting operations, one has to consider the complex interaction of alloying elements, tool materials, and process parameters.

The impacts of the most important alloying elements on the machinability of steel materials are described in the first section. In the following, practical challenges when cutting high-alloyed steel and stainless steel are presented based on the material's microstructure, which is determined by the carbon content, the alloying elements, and the applied heat treatment. Eventually, due to their high industrial relevance, some practical approaches concerning cutting parameters, tool materials, and the application of cutting fluids are presented in order to improve the machinability of austenitic stainless steels.

### Alloying Elements

Since manganese (Mn) forms hard carbides with carbon, Mn increases the strength of steel. It can be estimated that adding 1% manganese will result in an increased strength of 100 $N/mm^2$ (Klocke 2010). Accordingly, higher cutting forces can be detected for steels, which contain greater contents of manganese and carbon. The $Mn_3C$ inclusions are also responsible for an impaired machinability due to the increased tendency for abrasive tool wear.

Since manganese has a high affinity to sulfur (S), the formation of manganese sulfides (MnS) is very likely when adding Mn as an alloying element. Manganese contents of up to 1.5% facilitate the machinability of steels with low amounts of carbon (Klocke 2010). Especially, the chip formation, surface quality, and the resistance against the formation of built-up edges can be improved. The machinability of steels with low sulfur and thus manganese sulfide contents can be improved by the application of high feed rates, chip breaker geometries, and tool nose radii, which are smaller than the depth of cut (Biermann and Felderhoff 2010).

Higher lengths of MnS inclusions result in the reduction of certain mechanical properties such as strength, failure strain, and fatigue strength. These effects are especially detectable when the inclusions are transversely oriented to the direction of the deformation. Adding tellurium (Te) and selenium (Se) hinders the extension of these deformation-related MnS inclusions and therefore prevents the loss of strength and deformability to some extent (Klocke 2010).

Abrasive tool wear is also increased by the alloying elements chrome, molybdenum, and tungsten (Cr, Mo, W), which all tend to form hard carbides in steels with greater carbon contents. These carbides plough into the surface of the cutting tool, which eventually results in shorter tool life.

As long as there are no stronger deoxidation agents, silicon (Si) and oxygen ($O_2$) tend to form hard silicate inclusions, which show a similar impact on abrasive wear as Cr, Mo, and W. Si also increases the strength of ferrite, which results in higher cutting forces.

Chrome contents of 10.5–12% are responsible for the excellent resistance to corrosion of stainless steels. A thin film (ca. 5 nm, Bargel and Schulze 1994) of chromium oxide, formed by a reaction of the metal and the environment, acts

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as a barrier between the bulk material and the ambient medium and thus hinders corrosion (Peckner and Bernstein 1977).

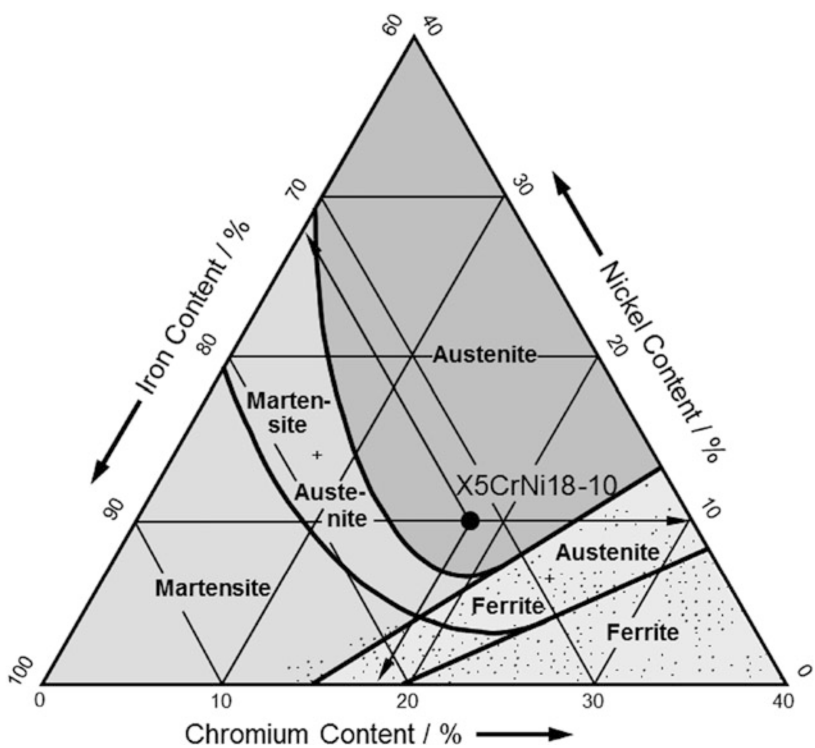
The alloying element nickel (Ni) increases the strength and the toughness (especially at low temperatures) of steel materials at the same time. Nickel combined with chrome stabilizes the austenitic phase zone to lower temperatures. The microstructure of low-alloyed steel changes from austenite to ferrite and perlite when being cooled down slowly below the Ac3 temperature of 723 °C. Due to its low thermal conductivity, high work hardening rates, high strengths, and ductility, austenitic steels are more challenging to machine than ferritic or perlitic ones (Korkut et al. 2004).

## Challenging Machinability of High-Alloyed Steel and Stainless Steel

Based on their microstructure, stainless steels can be subdivided into ferritic, martensitic, ferritic-austenitic, and austenitic steels. The microstructure and thus their machinability mainly depend on the alloying elements of chromium and nickel. Stainless steels contain at least 10.5% chromium and a maximum of 1.2% carbon (Klocke 2010). Figure 1 shows which microstructure can be expected when changing the chromium and nickel contents. For example, steels with 18% chromium, 10% nickel, and 72% iron (X5CrNi 18-10) usually show an austenitic structure after quenching.

The machinability of ferritic stainless steels is considered to be relatively good since the detectable adhesive and abrasive tool wear is small (Klocke 2010).

High-alloyed steels with a martensitic microstructure show machining results, which heavily depend on the workmaterial hardness and thus on the applied heat treatment. However, hardened and tempered martensitic stainless steels can be machined relatively well with suitable cutting parameters, tool materials, and coating systems, respectively. The dominant failure modes when using coated carbide tools for cutting hardened martensitic stainless steel are nose wear and chipping/fracture of the cutting edge. Especially, under the application of cutting fluids,




**Machinability of High-Alloyed Steel and Stainless Steel, Fig. 1** Phase diagram of Cr-Ni-steels with metallographic constituent data after quenching (Ignatowitz 1997)

CVD-coated carbide tools show better results than PVD-coated carbide tools with longer tool life and little formation of white layers on the machined surface (Ezugwu and Olajire 2002). The dominant wear mechanisms for alumina-based ceramic cutting tools when machining martensitic stainless steel are flank wear for low cutting speeds and crater wear or notch wear for high cutting speeds, respectively. Mixed alumina ceramic tools (e.g., $Al_2O_3$ + Ti[C,N]) show slightly higher tool life than zirconia and SiC whisker reinforced alumina-based cutting tools (Kumar et al. 2006).

Flank wear and catastrophic failure are the main tool failure modes when cutting tempered martensitic stainless steel using coated cermet tools. Abrasive and adhesive mechanisms lead to the flank failure mode while a combination of abrasion, adhesion, diffusion, fracture, and plastic deformation results in catastrophic tool breakage. The application of coated carbide tools mainly shows end clearance wear and flank wear. Negative side cutting edge angles result in a better wear behavior of both coated carbide and coated cermet tools, especially when machining at high feed rates (Noordin et al. 2007).

Duplex steels (hybrid martensitic-austenitic microstructure) are usually hard to machine due to their high deformability, strain hardening rates, and dominant tendency towards adhesion (Klocke 2010). Especially, the machinability of hot isostatic pressed (HIP) P/M duplex stainless steels is critical since increased oxygen contents and thus great amounts of oxide inclusions cause severe tool wear. In fact, tool life is decreased by as much as 40% when drilling HIP P/M duplex steel instead of conventionally produced stainless steel using solid carbide tools with internal coolant supply. Nevertheless, the formation of built-up edges remains the dominant tool failure mechanism for both steel grades (Paro et al. 2001).

Austenitic stainless steels are by far the most widely used high-alloyed steels in the industry. Like duplex steels, the machinability of austenitic stainless steels can be problematic due to high plasticity, low thermal conductivity, and a tendency to form build-up edges (Endrino et al. 2006). Thus, unfavorable chip forms like ribbon and snarled chips, high tool wear rates, and bad surface qualities can be detected. The low thermal conductivity is responsible for high temperatures in the tool-chip interface. The heat, which is generated in the primary and secondary shear zone, cannot be absorbed by the surrounding workmaterial fast enough and consequently causes thermally trigger wear mechanisms like the formation of craters on the rake face. This is especially valid for uncoated cemented carbide tools, which are still widely used to machine austenitic stainless steels. As a consequence, the applied cutting speeds are 2–5 times smaller than for the machining of ferritic-perlitic steels. Applicable cutting speeds range from $v_c = 50$ m/min (X5NiCrTi26-15) to $v_c = 160$ m/min (X6CrNiMoTi17-12-2), depending on the alloy. Under these circumstances, the expected tool lifetime is between 5 and 15 min (Klocke 2010).

### Practical Approaches to Improve the Machinability of Austenitic Stainless Steel

Due to their exceptional industrial relevance, some practical approaches to improve the machinability of austenitic stainless steels are presented in the following. They can be subdivided into attempts to modify the cutting tool geometries and coating systems, attempts to determine optimal cutting parameters, and attempts for the most suitable application of cutting fluids.

One geometrical tool feature, which leads to improved chip formation and chip breakage when cutting austenitic stainless steel, is the cutting edge radius (Klocke 2010). The sharper the cutting edge, the lower the applied deformation in the workpiece rim zone. Accordingly, the detected surface qualities increase with decreasing cutting edge radii. Additionally, the formation of burrs is hindered due to the lower deformations. This leads to ideal cutting edge radii of ca. 30 μm for finishing and 40–60 μm for roughing (Klocke 2010). Positive rake angles also extend tool life and improve surface finish (Belejchak 1997). This is due to a less-severe deformation, which is applied to the workmaterial.

Hard coating layer systems are able to improve the wear behavior of turning tools when cutting austenitic stainless steel as well as the resistance against built-up edges. The applied methodology to generate the coating plays an important role. The high process temperatures of the chemical vapor deposition (CVD) may decrease the fracture toughness of cemented carbide substrates while the lower temperatures during physical vapor deposition (PVD) make it possible to retain sharp cutting edges (Knotek et al. 1992). Refining the crystalline structure of the coating material leads to lower abrasive wear rates with respect to flank wear. For example, when end milling X5CrNiMo17-12-2 using a cemented carbide tool, the possible length of cut of a nanocrystalline AlTiN coating is twice as long as the one of a fine-grained coating of the same material (Endrino et al. 2006). The tool life can further be improved by surface postdeposition treatment, which removes macroparticles on the surface of the coatings (Bouzakis et al. 2001).

Concerning the determination of optimum cutting parameters for machining austenitic stainless steel with coated cemented carbide tools, increasing cutting speeds improve the surface roughness until a minimum is reached (ca. $v_c = 180$ m/min, Korkut et al. 2004), beyond which they worsen (Ciftci 2006). The higher surface roughness at low cutting speeds is mainly due to the formation of built-up edges and chipping of the cutting edge. The optimum surface quality at medium cutting speeds is explained by a better tool wear behavior due to a more efficient dissipation of heat. The tool-chip contact length also shows a minimum at cutting velocities of ca. $v_c = 180$ m/min and therefore results in a reduced wear rate (Korkut et al. 2004).

Usually cutting fluids are applied when cutting austenitic stainless steels. They provide lubrication in the tool-chip interface and remove the heat generated in the primary and secondary shear zone, which reaches high concentrations for stainless steels due to typically low heat conductivities. The vast majority of the used cutting fluids are based on mineral oils. Nevertheless, the application of vegetable-based cutting fluids can result in a better surface roughness and lower flank tool wear concerning turning processes with cemented carbide tools. Furthermore, the present trend towards vegetable-based oils and esters seems justified by a higher biodegradability and lower environmental impact (Xavior and Adithan 2009). Vegetable-based cutting fluids can also show better performances than commercial mineral-based oils when being used for drilling operations of austenitic stainless steel. An increase of tool life of as much as 177% can be detected only due to change of cutting fluids (Belluco and De Chiffre 2004).

## Cross-References

► Cutting Fluid
► Cutting, Fundamentals
► Machinability
► Wear Mechanisms

## References

Bargel H-J, Schulze G (1994) Werkstoffkunde [Materials engineering]. VDI Verlag, Düsseldorf
Belejchak P (1997) Machining stainless steel. Adv Mater Process 152(6):23–25
Belluco W, De Chiffre L (2004) Performance evaluation of vegetable-based oils in drilling austenitic stainless steel. J Mater Process Technol 148(2):171–176
Biermann D, Felderhoff F (2010) Process design for the efficient machining of high-performance steels. Stahl und Eisen 2:45–48
Bouzakis K-D, Michailidis N, Hadjiyiannis S, Efstathiou K, Pavlidou E, Erkens E, Rambadt S, Wirth I (2001) Improvement of PVD coated inserts cutting performance, through appropriate mechanical treatments of substrate and coating surface. Surf Coat Technol 146–147:443–450
Ciftci I (2006) Machining of austenitic stainless steels using CVD multi-layer coated cemented carbide tools. Tribol Int 39:565–569
Endrino JL, Fox-Rabinovich GS, Gey C (2006) Hard AlTiN, AlCrN PVD coatings for machining of austenitic stainless steel. Surf Coat Technol 200(24):6840–6845
Ezugwu E-O, Olajire K-A (2002) Evaluation of machining performance of martensitic stainless steel (JETHETE). Tribol Lett 12(3):183–187
Ignatowitz E (1997) Werkstofftechnik für Metallberufe [Materials engineering for metal workers]. Europa Lehrmittel, Haan-Gruiten

Klocke (2010) Manufacturing processes 1– cutting. Springer, Heidelberg
Knotek O, Löffler F, Krämer G (1992) Multicomponent and multilayer physically vapour deposited coatings for cutting tools. Surf Coat Technol 54–55:241–248
Korkut I, Kasap M, Ciftci I, Seker U (2004) Determination of optimum cutting parameters during machining of AISI 304 austenitic stainless steel. Mater Des 25(4):303–305
Kumar AS, Durai AR, Sornakumar T (2006) The effect of tool wear on tool life of alumina-based ceramic cutting tools while machining hardened martensitic stainless steel. J Mater Process Technol 173(2):151–156
Noordin MY, Venkatesh VC, Sharif S (2007) Dry turning of tempered martensitic stainless tool steel using coated cermet and coated carbide tools. J Mater Process Technol 185(1–3):83–90
Paro J, Hänninen H, Kauppinen V (2001) Tool wear and machinability of HIPed P/M and conventional cast duplex stainless steel. Wear 249(3–4):279–284
Peckner D, Bernstein IM (1977) Handbook of stainless steels. McGraw-Hill, New York
Xavior MA, Adithan M (2009) Determining the influence of cutting fluids on tool wear and surface roughness during turning of AISI 304 austenitic stainless steel. J Mater Process Technol 209(2):900–909

## Machinability of Non-rusting Steel

► Machinability of High-Alloyed Steel and Stainless Steel

## Machinability of Unalloyed Steel

► Machinability of Carbon Steel

## Machine

► Mechanism

## Machine Hammer Peening

► Peening

## Machine Scheduling

► Scheduling

## Machine Tool

Masahiko Mori, Adam Hansel and Makoto Fujishima
Mori Seiki Company, Aichi, Japan

### Synonyms

5-axis; Five-axis; Lathe; Mill; Milling machine; Spindle; Turning machine

### Definition

A **machine tool** is a machine used to make manufactured components in various utilizing a subtractive cutting process. Machine tools contain the four basic elements of the manufacturing process which are an energy source for constrained relative motion, a means to keep the work secure, a means to secure and orient the tool, and a means to control the previous means. Machine tools perform conventional machining or grinding on metal and other difficult to form materials (i.e., metal cutting by shear deformation, producing swarf). Machining may be accomplished with either a milling or turning process or a combination of both. The precise definition of a machine tool varies slightly from application to application, but it can be said that a machine tool is used to directly or indirectly make every modern man-made object. All manufacturing machines and objects are made and operate due to components made on machine tools including other machine tools. As such, machine tools are often called “mother machines.”

M

## Theory and Application

### History

Machine evolution is a result of continuously striving to improve on current process for the production of goods used to advance the fortunes civilization. Over many millennia, manufacturing processes gradually grew in terms of efficiency and repeatability. These advancements evolved into the modern machine tools available today.

Machines in the most simple of forms utilizing the basic fundamentals of modern machine tools have been existing for many thousands of years. Examples are bow drills and potter's wheels found in ancient Egypt and pole lathes from before the industrial revolution. Modern concepts of a machine tool began to emerge around the sixteenth century when screw-cutting lathes were developed. Various advancements such as metal frames, more accurate pitch control, and more sophisticated power sources all contributed to the steady advancement of machining ease and improved quality (Rolt 1965) (Fig. 1).

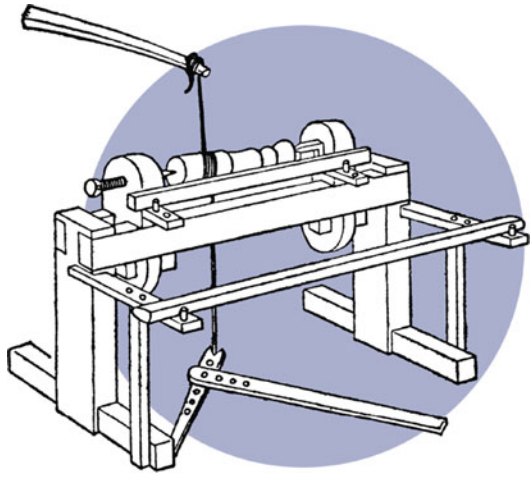
Near the start of the nineteenth century, these machines developed into a class of machines used as tools in the making of other machines. Modern machine tool builders who specialize in building machine tools for others use evolved into what we know today from efforts by inventors and entrepreneurs such as Henry Maudslay (credited with advancing the controllability of machine tools), John Wilkinson (development of a stable cylinder boring machine), and Isambard Brunel (introduction of production block-making machinery) (Roe 1987).

Today, from the simplest to the most complex, all machines are made and operate, thanks to components made on machine tools. Machine tools have become a foundational technology to all manufacturing and, in turn, to life as we know it.

### Theory and Description

#### Conventional Machining Processes

Machine tools are mechanical structures on which cutting is done. They utilize multiple moving (linear and rotational) axes providing relative motion, means to secure and orient the tool, means to control the workpiece, and means to control the energy source and the means above. Construction of typical machines tools consists of a base structure on which the frame is built called a bed. A column sits on the bed and is a structural element that supports the spindle/cutting tool and any axes on the spindle tool side. On the work side, a table for securing the work is positioned above a saddle which allows the table to have relative motion in regard to the tool. Servo motors driving ball screws provide the means for axis motion, and a CNC provides continuous control of each servo motor which enables sophisticated motion control between the tool and work. While numerous combinations of machine tool construction exist, they all utilize various designs of basic components described above (Boothroyd and Knight 1988).



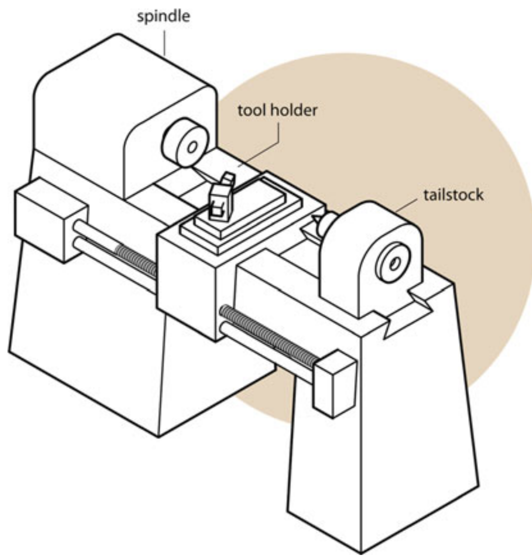
**Machine Tool, Fig. 1** Early pole lathe for wood turning

Two fundamental configurations of machine process drive the design and axis configuration of machine tool: turning and milling. The basic shape of the workpiece determines which process is the most appropriate. Turning machines are called lathes and rotate the workpiece while keeping the tool stationary. The workpiece is often supported at the opposite end of the chuck by a tailstock. The tool is mounted on a tool post through which the X-axis passes. The Z-axis passes through the center of rotation of the spindle. The tool post is attached to a drive mechanism that moves both in the X and Z directions and may also be configured with a Y-axis for more complex workpieces.

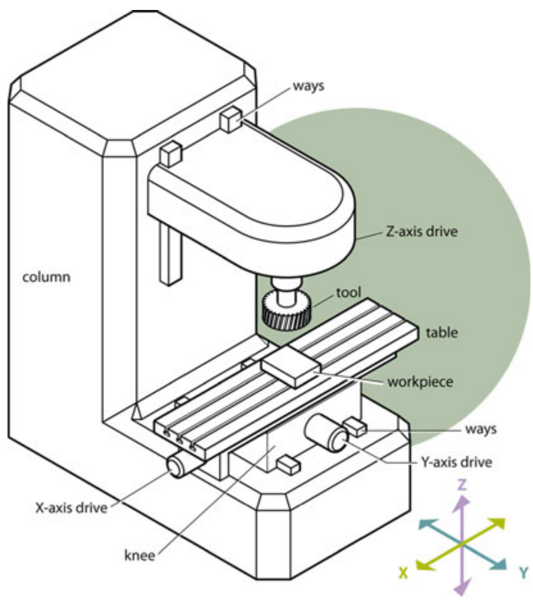
Milling machines are called mills and rotate the tool at high speed while keeping the workpiece stationary. Universally accepted nomenclature for the axes defines the X-axis as the longest axis travel parallel to the table with the Y-axis as the shortest axis travel parallel to the table. The Z-axis represents motion parallel to the spindle rotation axis, that is, motion normal to the XY-axis plane. Milling machines are most typically composed of three linear axes and called 3-axis machines. However, two or more rotational axes may be installed for complex relative tool/work motion and are referred to as 5-axis machines (Figs. 2 and 3).

Linear guiding mechanisms for machines normally use either slideways or linear guides. Slideways (or boxways) are typically found in machines requiring heavy-duty cutting ability over repeatability and axis speed. Precision-formed metal guides with special coatings slide against each other on an oil film and provide very high rigidity and damping during the cutting process. Linear guides are essential linear ball bearings utilizing recirculating ball bearings to achieve very low friction and high-speed axis movement. Since linear guides have low damping characteristics, their trade-off for high-dynamic motion is lower rigidity and lighter-duty cutting than slideways (Slocum 1992).

Machine tool drives for linear axes are commonly composed of a servo motor, coupling, ball screw, and support bearings. Ball screws used nuts with recirculating ball bearings under preload to achieve precise axis positioning. By preloading the screw during installation, very high linear stiffnesses can be introduced. Heat generation in the ball screw can simply be controlled by directing a cooling fluid through the center of the ball screw. Linear motors have been utilized for machines requiring very high-dynamic motion or very high accuracy and repeatability, but the cost of the permanent magnets in the linear motors has kept them from being utilized on a widespread basis. Massive heat generation and attraction of ferrous chips has also been an obstacle to widespread linear motor adoption, although new designs are solving these issues more regularly (Slocum 1992).




**Machine Tool, Fig. 2** Simple lathe with spindle, tailstock, and tool




**Machine Tool, Fig. 3** C-frame type 3-axis milling machine

### Multi-axis and Integrated Machine Platforms

Many more combinations and additions of axes are possible, but not covered here. Recent advancements have been the widespread trend to 5-axis machines and also to combine milling and turning machines into multi-axis machines using either a lathe as the base platform or a mill as a base platform (mill-turn). These machines are used for very complex workpieces or to reduce the number of setups needed to complete a single workpiece.

Five-axis machining centers equip with two additional rotary axes besides traditional 3-axis milling machines' X, Y, and Z linear axes. The rotary axes tilt the cutting tool with respect to the workpiece. There are different ways of machine configurations to accomplish the rotary motion. Five-axis machines are capable of machining complex sculptured geometries by simultaneously controlling five axes by a sophisticated CNC controller which is made possible by advancements in CPUs. Oftentimes, 5-axis machining centers are used for indexing tool/workpiece to access features at different angles and on different faces of the workpiece. This is called 3 + 2 machining. With the unique feature of 5-axis machining center, a complex part can be machined in a single workpiece setup, and thus the machine contributes to dramatically improve manufacturing time, cost, and accuracy of parts.

A mill-turn machine has features of both milling and turning CNC machines. Similar to 5-axis machining centers, all necessary machining operations of complex parts can be done in a single workpiece setup. It contributes to improve the part productivity and to reduce necessity of having a variety of machines on a shop floor. Adding a milling spindle to a conventional NC turning machine is the typical machine configuration available today. It often has an additional rotary axis on the spindle head to rotate the spindle head, to index the tool, and to simultaneously control the tool angle with other linear axes achieving complex multi-axis movement. Having a turning feature on a machining center is another type of mill-turn machines. The milling spindle needs to hold a turning tool, and the machine is required to have a high-speed rotary table to achieve sufficient cutting speed during turning applications (Fig. 4).

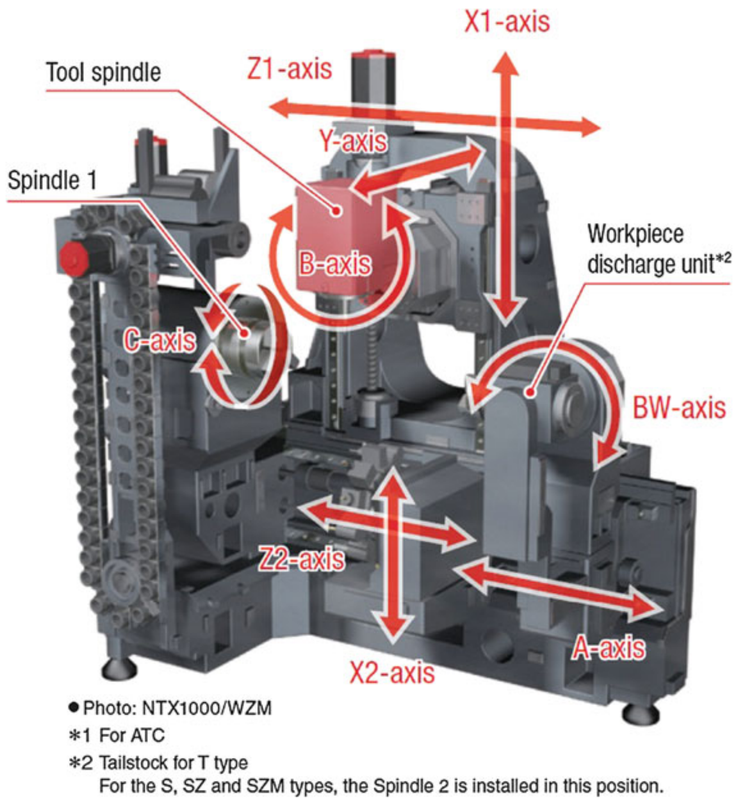
#### Nontraditional Machining Processes

In addition to conventional machine tools, nontraditional machine tools such as a laser machine and ultrasonic machines have become more and more popular in industries. Instead of physical interaction between a cutting edge and a workpiece, a laser machine uses laser light to remove materials from the part. Therefore, material removal process can be completed without any mechanical contact. The unique process accomplishes high process stability and repeatability, and no tool wear or breakage is required to take into account throughout the laser machining process. Laser machines can be used for shaping, producing precision cutting edges of PCD/CVD/CBN tools, fine cutting for thin metal sheets/tubes, drilling, etc. The working principle is melting and vaporizing materials through heat created by intense energy of the laser. A variety of laser types are used for such laser machines including YAG, Q-switched laser, fiber laser, and $CO_2$ slab laser (Tlusty 2000).

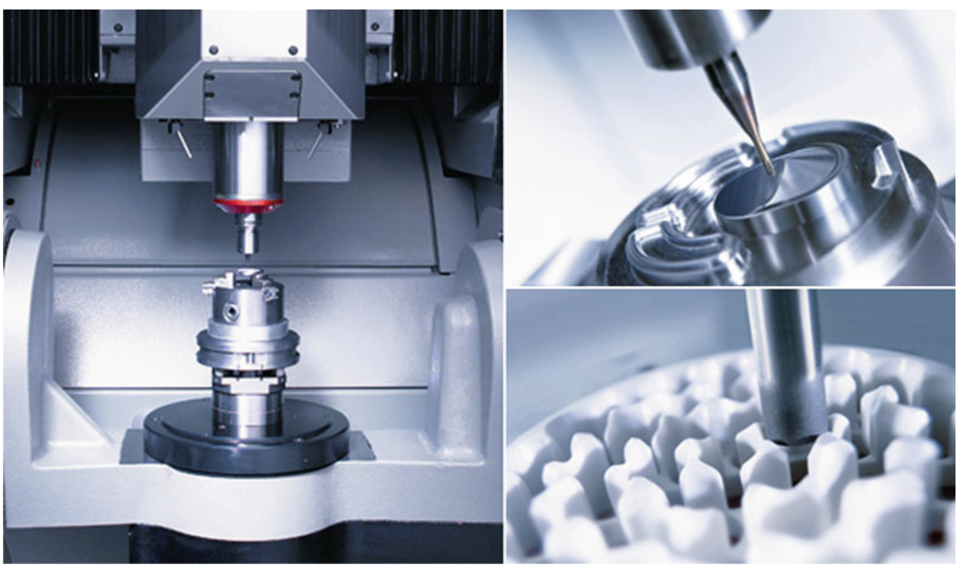
Ultrasonic vibration-assisted milling machine is one of the future-oriented technologies for diverse industries to meet their increasing demands. Due to the kinematic overlapping of tool rotation with added high-frequency oscillation on the cutting tool, high-performance materials that pose difficulties for metal-removal technology using conventional methods can be successfully machined efficiently and with perfect results. Reduced process forces thanks to high-frequency vibrations permit the manufacturing of thin wall, lead to longer tool life, and significantly reduce micro-cracks in the materials, and surface quality can be easily achieved with the machine (Tlusty 2000) (Figs. 5 and 6).

Rotary ultrasonic machining (RUM), often referred to as simple ultrasonic machining, is a hybrid process in which ultrasonic axial impact machining is combined with diamond impregnated grinding. RUM is uniquely suited to the machining of advanced ceramics, technical glasses, composites, and many other hard and brittle materials previously considered difficult to machine. Through the superimposition of tool rotation and high-frequency axial oscillation, material removal rates, tool wear, and surface

**Machine Tool, Fig. 4** Axis structure of Mori Seiki mill-turn NT1000

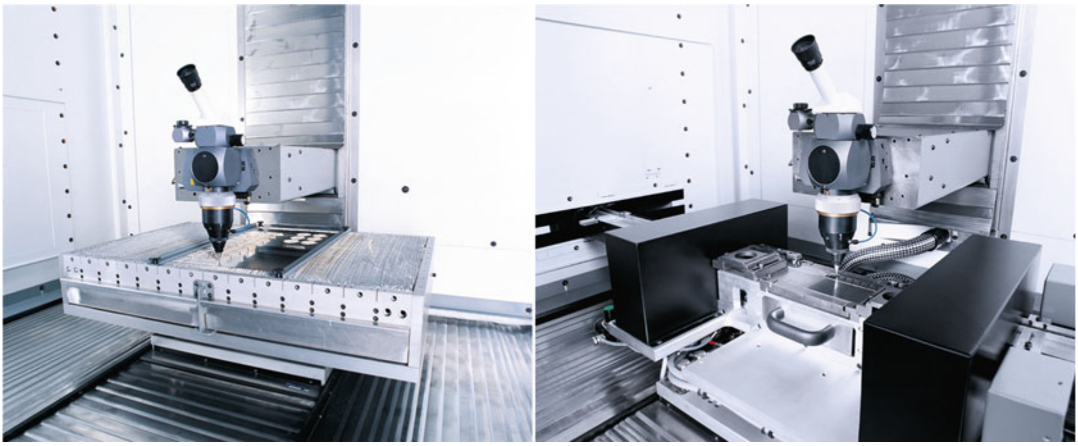




**Machine Tool, Fig. 5** Ultrasonic machining example

finishes, greater than the sum each tool actuation combined, have been observed. In addition, and of critical interest to hard and brittle machining, is the reduction of cutting forces observed through the application of ultrasonic actuation. Reduced process forces enable the manufacturing of thin-



**Machine Tool, Fig. 6** Laser machining example

walled structures at a much high rate of production and with decreased risk of critical fracture of the workpiece.

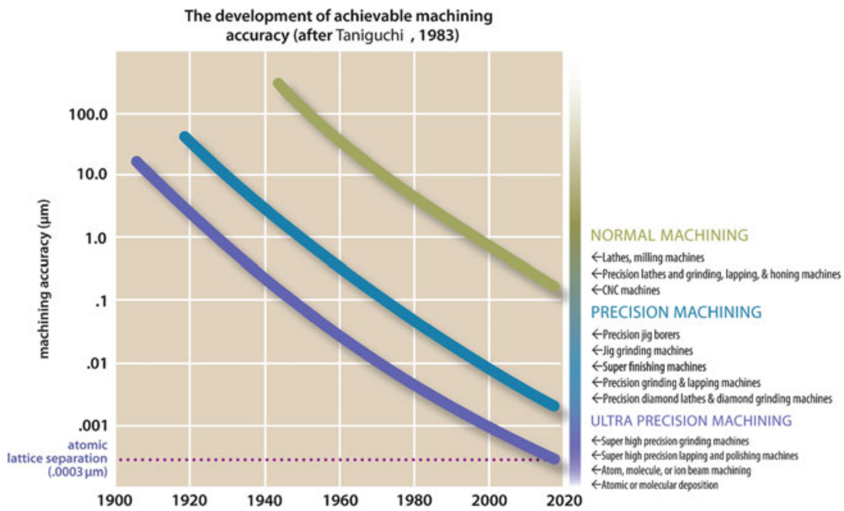
Additive manufacturing (AM) is a set of processes used to build objects from a digital model and raw material, without molds or foundry tooling. The broad field of AM includes many different process for a wide variety of materials. The primary processes for nonmetals are extrusion deposition, granular materials binding, lamination, and photopolymerization. For metallic applications the two basic methods are powder bed and powder spray (also known as directed energy deposition). In powder bed machines, a laser is used to scan and melt metal powder which is leveled in a bed in successive layers. Conversely, in powder spray machines, the metal powder is sprayed into the melt pool created by the traversing laser. Powder bed is typically preferred for small-scale deposition of high complexity and powder spray for larger-scale work and higher deposition rates (higher by more than an order of magnitude). Hybrid machines supporting AM and SM (subtractive manufacturing) enable the use of the more productive powder spray process while providing the required accuracy with robust milling, turning, and grinding processes.

Accuracy progression of machine tools is described in the classical Taniguchi chart for micromanufacturing. As manufacturing processes have improved, machine tools have been able to reduce the amount of material affected by each process to create finer and finer product features, resulting in higher and higher degrees of accuracy which is a combination of the precision of the X-, Y-, and Z-axis as well as the B- and C-axis for 5-axis machining (Dornfeld and Lee 2008) (Fig. 7).

### NC Control Concept

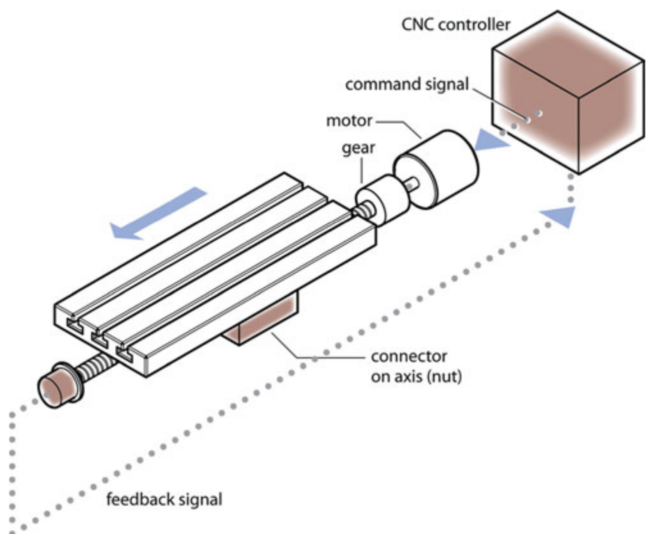
Control of a machine tool's motions by CNC allows very sophisticated movement and part manufacturing. The control system uses a geometric representation of the parts surface to be machined and considers the orientation of the work surface and tool inclination to send commands to each drive on the machine's axes after the tool path is interpolated. The CNC controls the position of the axes as well as the speed of motion as cutting speed and feed are important parameters for creating parts with the desired accuracy and finish. In order to ensure the machine is moving as commanded by the CNC, the CNC measures the actual position through feedback sensors known as encoders which can measure servo motor rotation or actual linear position of the axis (Tlusty 2000) (Fig. 8).

In order to control a machine tool by CNC, a program must be created and input into the CNC. CAM (computer-aided manufacturing) is the software that is used to create complex tool paths and




**Machine Tool, Fig. 7** Deposition additive/hybrid machining examples

**Machine Tool, Fig. 8** Taniguchi machine accuracy progression chart






is used in all but the most simple operations for creating programs. A CAM software utilizes series of mathematical algorithms to derive a tool path required to shape the workpiece to the final state. Process knowledge is input at the CAM level in terms of speeds and feeds for material/tool combinations, proper tools for the desired application, the order of operations, and so on. The tool path output by a CAM system is generic in nature and must be post processed to apply to a specific machine parameters and axis configuration. Post processing converts the CAM tool path to a series of commands written in G-code which is a universal machine tool programming language.

### Machine Tool Design Evolution and Tools

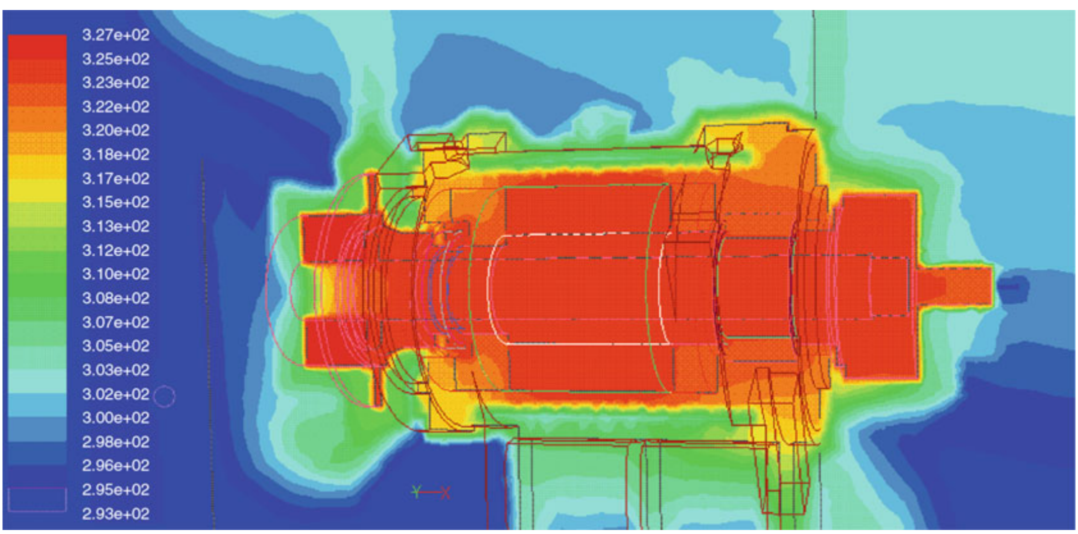
Even the most robustly designed machine tools with the most accurate assembly and best part program still exhibit error. Repeatable errors such as imperfectly straight axes can be measured and compensated out at the machine control level. Other unrepeatable errors require strict process control to keep to a minimum. As machine tools have grown in complexity over the last 10 years, so have the methods for design. 3D CAD is now the industry standard, and virtual modeling and simulation are commonly used to verify models prior to actual prototype production. Such technology is essential to producing machine tools with adequate rigidity for complex structures and movement. An example is thermal distortions caused by fluctuations in room temperature and operation of the motors, gears, pumps, electronics, and so on. Small changes in machine tool temperature cause growth or shrinkages resulting in unknown displacement between the cutter and the work which in turn causes dimensional errors in the part. Modern machines are designed to minimize such effects by careful design and analysis prior to building the machine as well as an array of temperature control methods (Dornfeld and Lee 2008) (Fig. 9).

## Peripheral Requirements

Just by themselves, machine tools have realized significant advancements over the last 10 years. This in turn has driven surrounding technology to greater heights as well. To keep up with potential productivity of modern machine tools with high-speed and high-power spindles, automation is being built into the work flow using various techniques such as linear pallet pools (LPP), robot loading/unloading, and automatic work changers (AWC). Work holding and fixture technology has advanced as well to offer much stronger holding ability and micron-level repeatability without causing large distortions in the workpiece. More productive machines with greater spindle uptime require better swarf control and chip conveyance which has prompted development of zero chip technologies and multifunction chip conveyors. These are but a few examples of the way peripheral technology has advanced in response to ever-increasing machine tool performance.

### Applications

Machine tools are able to supply an incredible variety of manufacturing products used in nearly every product we have in use in daily life. From transportation to medical, to energy, and to industrial machinery, machine tools play a vital role to ever-expanding productivity and product complexity and enable our modern society. From the first mass-produced Fords to today's jumbo airliners, machine tools created the necessary




**Machine Tool, Fig. 9** Typical ball screw-driven linear axis feed mechanism components and other machines efficiently and productively to a state that has allowed true globalization to the entire world population. Every year, the options available to consumers in all major industries become more complex and enjoyable while relying on ever-greater product standards. This is enabled by manufacturing technology and designs that allow greater production efficiency and higher-performing products due to tighter tolerances in machined components.

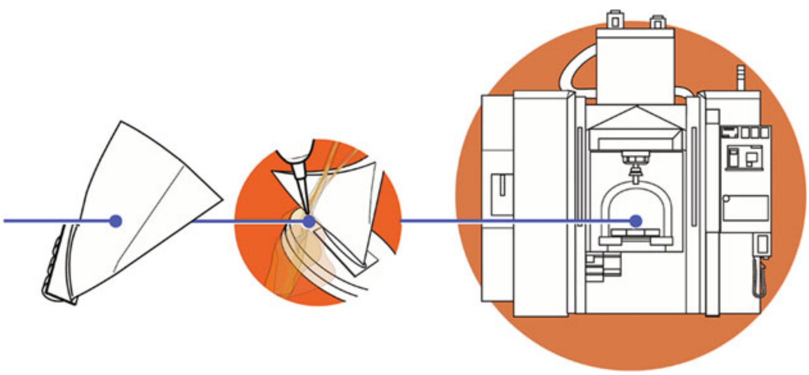
An example is the now commonplace procedure of joint replacement. Materials used to replace the bodies' original solutions are challenging to manipulate due to the toughness, wear, and biocompatibility requirements. Thus, the skill of the machinist and capability of the machine tool play an equal role to the skill of the surgical team in a successful surgery. The workpieces created are not simple but require sophisticated 5-axis or more machining, and extremely tight tolerances must be met to allow the joints to function indefinitely (Figs. 10, 11, and 12).

## Nomenclature and Key Terms

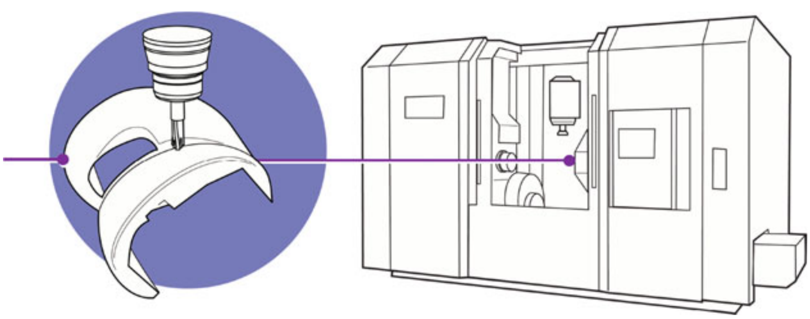
- **CNC** (Computer Numeric Control) – A control system where numeric values corresponding to a desired control position are interpolated by a computer.
- **Turning** – A machining method in which the workpiece rotates and the tool is stationary.
- **Milling** – A machining method in which the workpiece is stationary and the tool rotates.
- **Feed rate** – The rate of travel of a cutting tool across the work.
- **Chips** – Term for the waste product in subtractive machining processes.
- **Burr** – A portion of material, generally sharp, that is left after the cutting process.
- **Swarf** – The residue created from metal fabrication. In machining, swarf is synonymous with chips.
- **Ball screw** – A type of lead screw that with recirculating ball bearings between the screw and nut. This is the most driving mechanism used for linear axes of machine tools.
- **Fixture** – A device used to support and clamp work to the table of a machine tool.

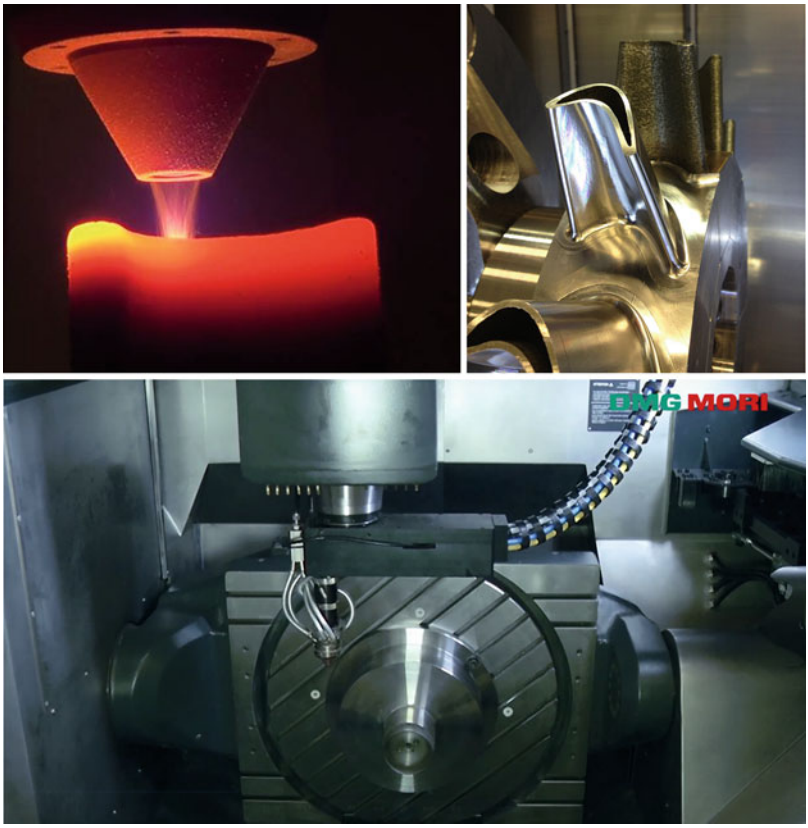


**Machine Tool, Fig. 10** Thermal analysis of lathe spindle



**Machine Tool, Fig. 11** Aerospace part






**Machine Tool, Fig. 12** Medical part

- **CAM** (computer-aided manufacturing) – The software used to program a tool path for the desired workpiece shape.
- **Post processing** – The conversion of tool path data to G-code based on the machine configuration and desired process.
- **G-code** – The most widely used CNC programming language used to operate a machine tool.
- **Finish** – The measure of integrity of the final surface after the machining process.
- **Bed** – The principle base of the machine tool supporting the other parts of the machine.
- **Column** – The structural part of the machine tool support axes on the spindle side.
- **Saddle** – A structural part of a machine tool that provides the interface between two linear axes.
- **Table** – A structural part on a mill that holds workpieces and fixtures.
- **Headstock** – On a mill or lathe, the headstock houses the spindle.
- **Chuck** – A device for axial clamping of rotary components, typically used to hold workpieces on a lathe.
- **Spindle** – The motor assembly that rotates the tool on a mill or the work on a lathe.
- **End mill** – Typical milling tool used in pocketing, slotting, and various feature creating operations.
- **Face mill** – Typical milling tool used for creating large, flat surfaces on workpieces.
- **Drill** – Typical tool used for creating holes in workpieces.
- **Tap** – Typical tools used for creating threads in a drilled hole.

## Cross-References

► Computer-Aided Design
► Computer-Aided Manufacturing
► Computer Numerical Control

▶ Electric Discharge Machining
▶ Grinding
▶ Tool Holder

## References

Boothroyd G, Knight W (1988) Fundamentals of metal machining and machine tools. CRC, Boca Raton
Dornfeld DA, Lee D (2008) Precision manufacturing. Springer, New York
Roe JW (1987) English and American tool builders. Yale University Press, New Haven. CT, 1916 (republished by Lindsay Publications, Bradley, IL)
Rolt LTC (1965) A short history of machine tools. MIT Press, Cambridge
Slocum AH (1992) Precision machine design. SME, Dearborn
Tlusty J (2000) Manufacturing processes and equipment. Prentice Hall, Upper Saddle River

### Further Reading

5American Precision Museum
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# Machine Tool Vibrations

▶ Chatter

# Machining

▶ Self-Propelled Rotary Tool

# Machining of CFRP/GFRP and Composite Materials

▶ Machinability of Carbon-Fiber-Reinforced and GLARE Materials

# Machining of Spheroidal Ductile Iron

Wit Grzesik
Department of Manufacturing Engineering and Production Automation, Opole University of Technology, Opole, Poland

## Synonyms

Ductile cast iron; Nodular cast iron; SG iron; Spheroidal graphite iron; Spherulitic graphite cast iron

## Definition

Spheroidal ductile iron is a type of cast iron invented in 1943 by Keith Millis. While most varieties of cast iron are brittle, ductile iron has much more impact and fatigue resistance, due to its nodular graphite inclusions.

## Theory and Application

Spheroidal cast iron materials are widely used in the automotive industry producing a variety of diesel engines which demand more ductile materials with specific spheroidal graphite inclusions distributed regularly into the different matrixes. Their tensile strength and the resistant to ductile fracture, and as a result their machinability rate, depend on the microstructure of the matrix. In consequence, cutting tools are subjected to intensive abrasive wear and, as a result, tool life is limited to several minutes and the surface finish is rapidly deterioriated. This important technological limit should be reduced by the applications of advanced cutting tool materials including silicon nitride ceramics, SiAlONs and CBN (cubic boron nitride) based materials.

## Recent History

In recent years the development of new cast iron materials has been seen to offer a greater competition to other materials and made cast iron a competitor to components not traditionally manufactured from this material (Schulz and Reuter 2001). As a result, visible progress in using iron grades with substantially improved mechanical and tribological properties, such as spheroidal (nodular) iron, GJS (equivalent German symbol – GGG); compacted graphite (vermicular) iron, CGI (equivalent German symbol – GGV); and the strongest grade, austempered ductile iron (ADI), can be noticed (Schulz and Reuter 2001; Byrne et al. 2003).

## State-of-the-Art and Application

## Introduction

### Characterization of Ductile Irons

As the desire for lightweight components grows caused by the need to achieve better fuel economy, there is an associated increase in the use of ductile iron and austempered ductile iron. Additionally, just on the horizon, there is an anticipated growth in the use of compacted graphite iron, especially in the truck industry, which relies upon diesel engines. Spheroidal cast iron (SCI) is also known as ductile and rarely as nodular iron. Some typical applications of various grades of iron with recommended cutting tool materials are specified in Table 1. The microstructures of three iron grades are presented in Fig. 1. Excellent mechanical and fatigue strengths of ductile irons result from globular graphite (Fig. 1b) or lamellar (vermicular) graphite (Fig. 1c) structures, respectively (Schulz and Reuter 2001; Byrne et al. 2003; Nayyar et al. 2012).

In contrast, classical gray iron has graphite inclusions in the form of flakes (Fig. 1a). Recently, such manufacturing sectors as machine building, automotive, and energy/wind power consume more ductile irons including spheroidal, vermicular, and ADI grades. Some automotive parts made of ductile irons selected in (Graham 2006) are presented in Fig. 2.

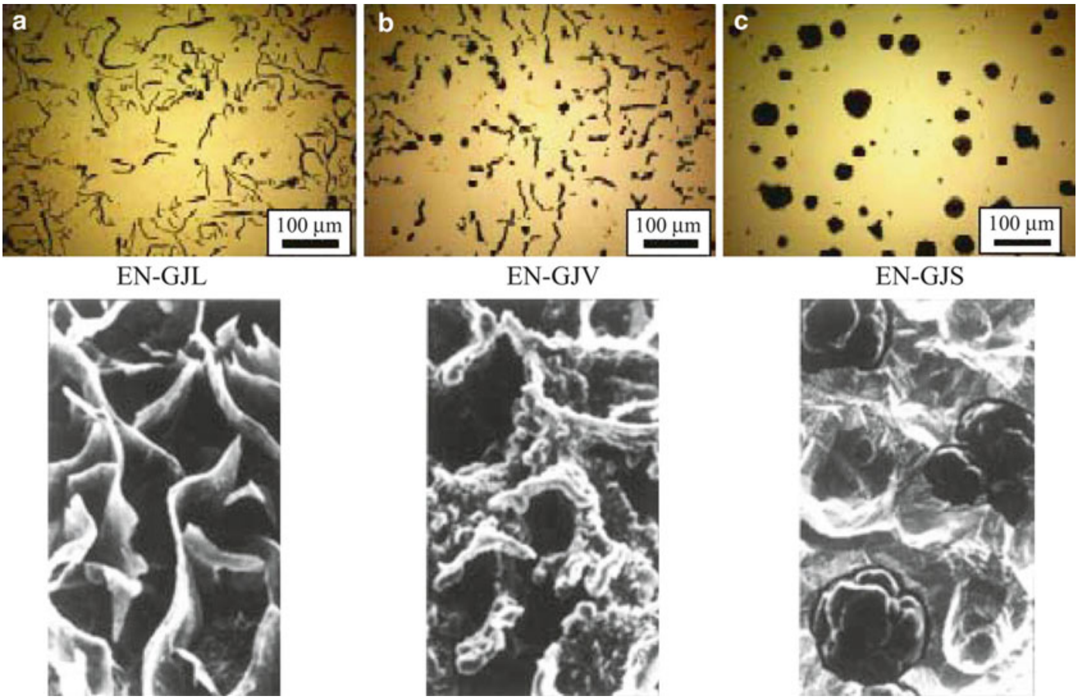
The classification of spheroidal iron grades in terms of their microstructures and mechanical properties (ultimate tensile strength vs. elongation at fracture) is presented in Fig. 3. The grade with the lowest UTS (ultimate tensile strength) (EN-GJS 400-15) has a poor ferritic (F) microstructure, whereas the grade with the highest UTS (EN-GJS 700-2) has a poor pearlitic (P) microstructure. Between them, the grades with mixed F-P or P-F microstructures are composed. In this study the grade EN-GJS 500-2 with mixed P-F microstructure (Fig. 4) was predominantly investigated. It is easily seen from Fig. 4 that graphite particles in the form of spheres are surrounded by ferrite (bright envelopes over them). This grade contains 3.78% C, 2.46% Si, and 0.32% Mn and consists of 50% pearlite, 40% ferrite, and 10% graphite. The ultimate tensile strength UTS = 500 MPa, the percent elongation at fracture A = 7%, and Brinell hardness are about 175HB.

### Characterization of Cutting Tool Materials

In general, machining of ductile irons is difficult due to their characteristic microstructure and high

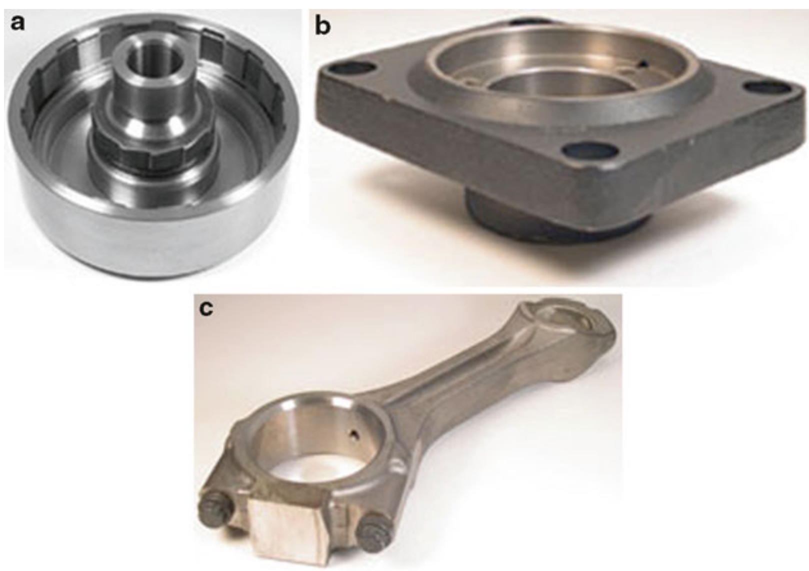
**Machining of Spheroidal Ductile Iron, Table 1** Application tendencies of cast irons and relevant cutting materials in automotive industry (Grzesik et al. 2009; Momper 1998)

| Iron grade | Trend | Typical parts | Typical cutting tool materials |
|---|---|---|---|
| Gray cast EN-GJL | Downward | Cylinder blocks, cylinder heads, and brake drums and disks | Carbide coated with $Al_2\,O_3$, silicon nitride $Si_3N_4$, CBN |
| Vermicular CGL | Upward | Cylinder blocks of diesel engines, retainers, and fasteners | According to process requirements |
| Nodular EN-GJS | Upward | Crankshafts, camshafts gear, wheels, cases, and housings | Multilayer MT-CVD and PVD-coated TiCN/$Al_2O_3$/TiN/$Al_2O_3$/TiN/TiCN carbides, cermets, mixed ceramics, $Si_3N_4$ ceramics, CBN |



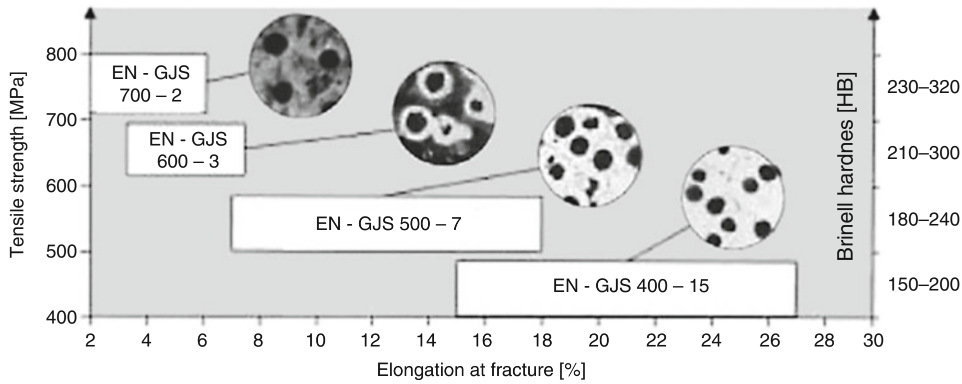

**Machining of Spheroidal Ductile Iron, Fig. 1** Possible graphite morphologies (SEM images): gray cast iron (**a**), compacted cast iron (**b**), spheroidal cast iron (**c**). Above adequate optical images after (Grzesik 2017) with modifications



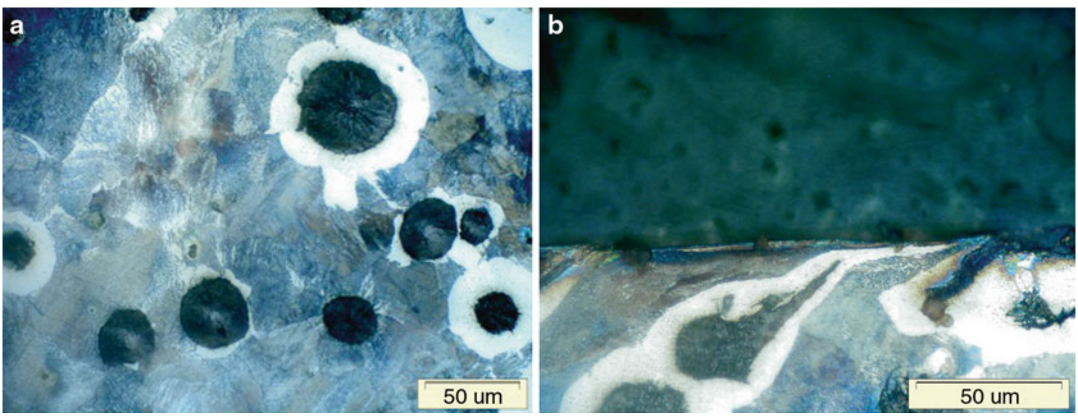



**Machining of Spheroidal Ductile Iron, Fig. 2** Typical automotive parts made of nodular iron: clutch housing (**a**), gearbox bearing cap (**b**), connector rod (**c**)

ductility, so in order to enhance the productivity of the abovementioned manufacturing sectors specially coated carbide, silicon nitride, SiAlON, and CBN, cutting tools (Byrne et al. 2003; Sandvik 1999; Schneider and Richter 2006; CeramTec 2017) are used. In the case of spheroidal iron due to characteristic two-phase microstructure with globular graphite inclusions and




**Machining of Spheroidal Ductile Iron, Fig. 3** Relationship between microstructure and mechanical properties for EN-GJS grades according to CLAASguss (2006) after modifications

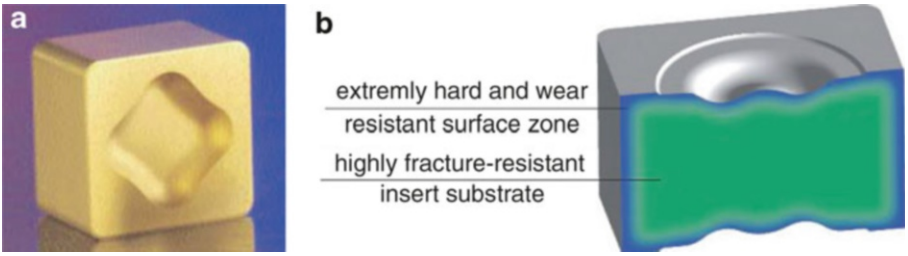



**Machining of Spheroidal Ductile Iron, Fig. 4** Microstructure of P-F nodular iron (**a**) and deformation of surface layer in cutting (**b**)

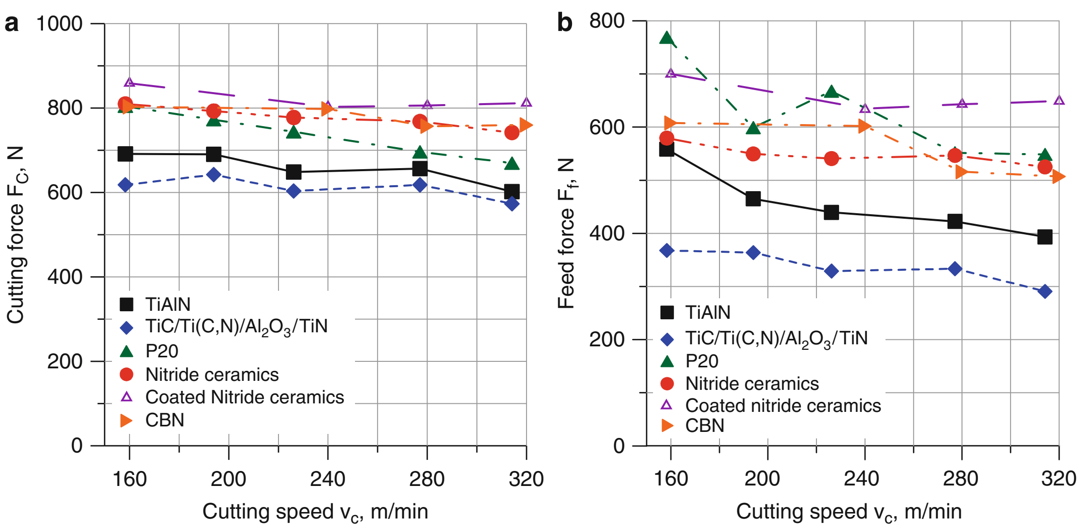
high ductility, more wear-resistant cutting tool materials such as multilayer coated carbides, uncoated and coated silicon nitride ceramics $Si_3N_4$ (coated with $Al_2O_3$/TiN), SiAlON, and L-CBN are recommended depending on the iron grade and machining conditions (Schneider and Richter 2006). Some examples of cutting tool inserts used in machining of SCI are presented in Fig. 5.

Silicon nitride ceramics, as hard covalent materials, have higher strength at higher temperatures and higher resistance to abrasive wear and improved chemical and oxidation resistance (Sandvik 1999; Holmberg and Matthews 1994; Grzesik 2017). Moreover, they are more resistant to thermal shocks and tougher than aluminum oxide-based ceramics. Under moderate cutting speeds, abrasive and adhesive wear predominantly occur in machining of all ductile iron materials (Byrne et al. 2003; Momper 1998; Abele et al. 2002). In order to increase tool life, the innovative α-/β-SiAlON and β-silicon nitride cutting materials are additionally protected by TiCN/Ti and $Al_2O_3$/TiN multilayer coatings, respectively (Grzesik et al. 2009; Grzesik 2008; Abele et al. 2002).

The silicon nitride-based ceramics were found to be an excellent choice for machining gray and ductile cast irons at cutting speeds over 400 m/min (Sandvik 1999; Schneider and Richter 2006; CeramTec 2017; Grzesik 2008). The technological experience in applying $Si_3N_4$




**Machining of Spheroidal Ductile Iron, Fig. 5** Multilayer TiCN/Ti-coated silicon nitride (**a**) and α-/β-SiAlON with gradient characteristic (**b**) inserts, concept after (CeramTec 2016) with modifications




**Machining of Spheroidal Ductile Iron, Fig. 6** Influence of cutting speed on the cutting (**a**) and feed (**b**) forces. Cutting parameters: nitride ceramics (f = 0.16 mm/rev, $a_p$ = 2 mm), coated nitride ceramics and CBN (f = 0.12, mm/rev, $a_p$ = 3.3 mm)

ceramic-based cutting tools to machine ductile cast irons is not enough to optimize the cutting process and increase tool life (Grzesik et al. 2009; Grzesik 2008; Grzesik and Żak 2009).

Especially, the economical dimension of using coated silicon nitride tools to machine ductile irons needs further in-depth investigations of tool wear and corresponding wear mechanisms to design optimal coatings.

## Characteristics of Cutting Process

### Cutting Forces

All machining tests were carried out on a CNC turning center. Experimental program includes measurements of the cutting $F_c$ and feed $F_f$ forces by means of the Kistler piezoelectric dynamometer model 9257A. Force signals were transmitted in online mode to the Kistler 5070 amplifier, and a PC with National Instruments LabVIEW 6i software was used to acquire and analyze data. The generated signals were recorded with the frequency of 1000 Hz.

Figures 6 and 7 show changes of the measured values of the cutting force for all tested cutting tools when varying cutting speed (Fig. 6a, b) and feed rate (Fig. 7a, b). As illustrated in Fig. 6a, the highest cutting forces were recorded for coated silicon nitride ceramic tools for which the $F_c$ force increases slightly up to 800 N when the cutting speed

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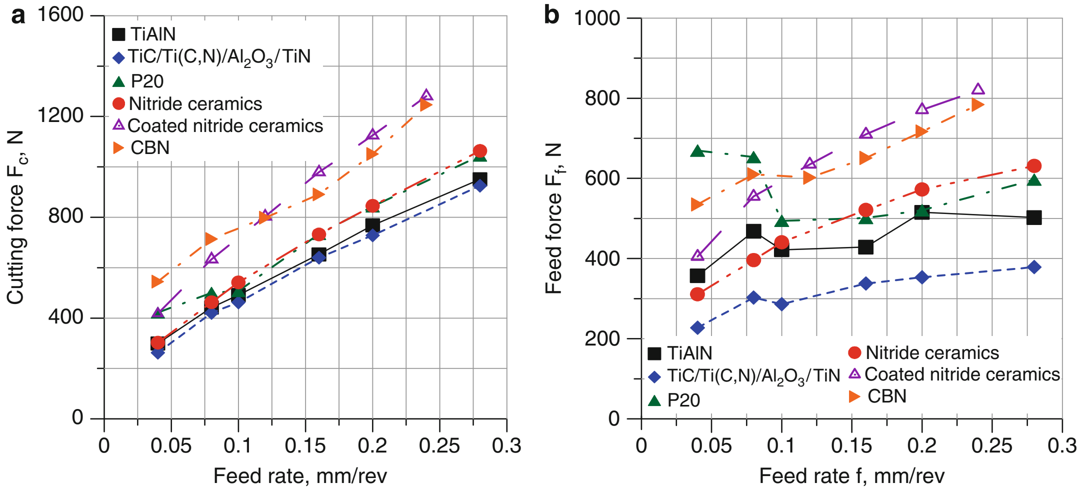
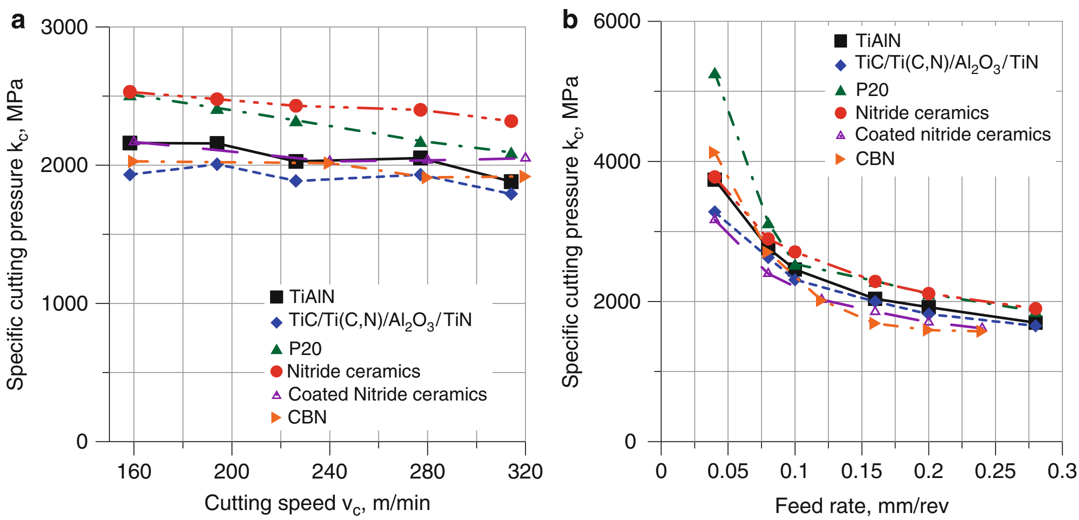



**Machining of Spheroidal Ductile Iron, Fig. 7** Influence of feed rate on the cutting (**a**) and feed (**b**) forces. Cutting parameters: nitride ceramics ($v_c$ = 280 m/min, $a_p$ = 2 mm), coated nitride ceramics and CBN ($v_c$ = 240 m/min, $a_p$ = 3.3 mm)

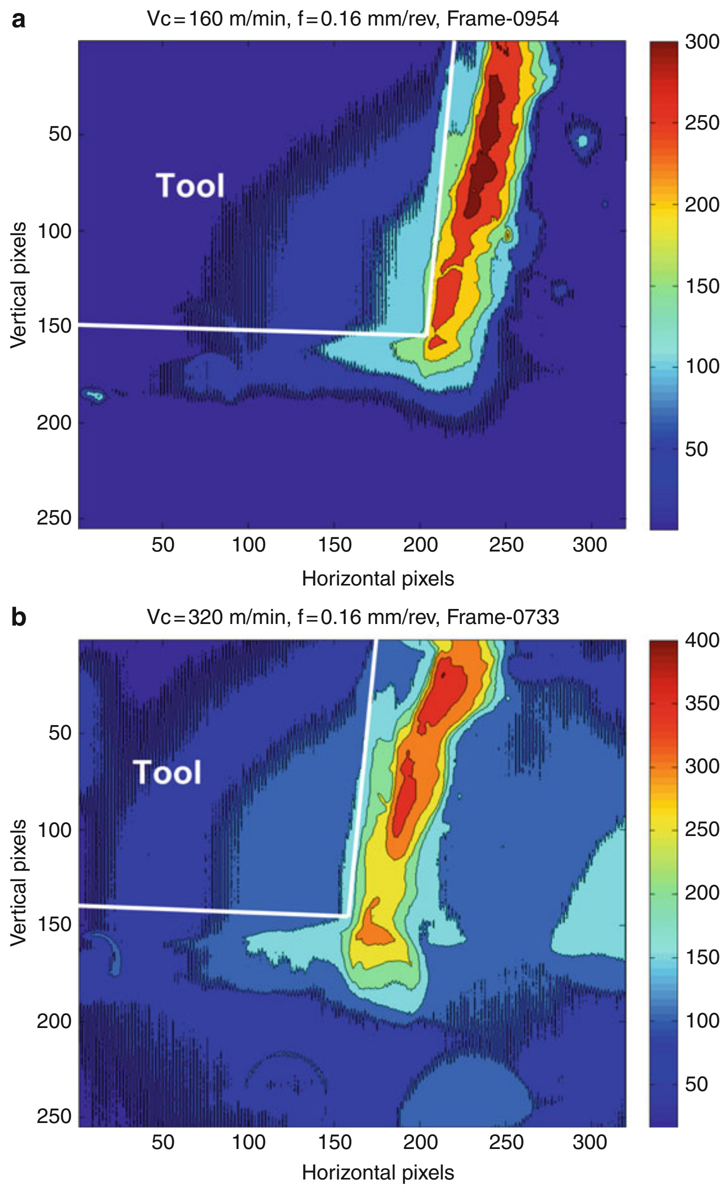



**Machining of Spheroidal Ductile Iron, Fig. 8** Influence of cutting speed (**a**) and feed rate (**b**) on specific cutting pressure

increases from 160 m/min up to 320 m/min. On the other hand, the lowest cutting forces were measured for multilayer coated tools for which the minimum friction coefficient was determined.

But for the latter case, the $F_c$ force does not decrease monotonically but varies about 600 ± 20 N. In general, the cutting force rises visibly with the increase of the feed rate; for example, for $Si_3N_4$ tools it increases from 300 N for f = 0.04 mm/rev to above 1200 N for the feed of 0.28 mm/rev.

In order to normalize the obtained force data, the specific cutting pressure was determined in terms of the cutting speed (Fig. 8a) and feed rate (Fig. 8b). In the case of $k_c$ versus $v_c$, the value of $k_c$ oscillates between 1800 MPa and 2500 MPa, but the lowest




**Machining of Spheroidal Ductile Iron, Fig. 9** Thermal images with temperature scale captured during cutting of SCI with silicon nitride cutting tools at variable cutting speed: 160 m/min (**a**) and 320 m/min (**b**). Own records presented also in (Grzesik et al. 2009)

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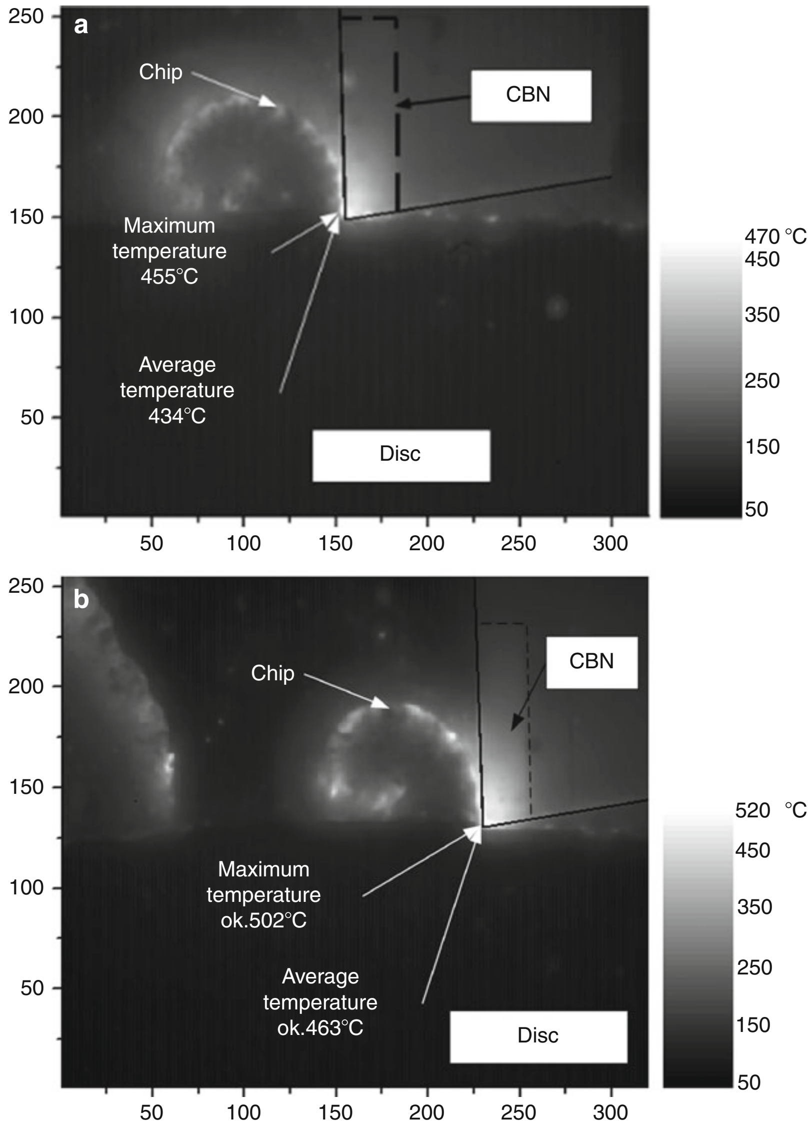
values of $k_c$ were determined for coated carbide and CBN tools.

This means that the specific cutting energy changes in the range of 1.8–2.5 GJ/m$^3$, which roughly agrees with relevant data provided for irons by Boothroyd and Knight (2006). In particular, for lower feed rates, as shown in Fig. 8b, the specific cutting pressure increases markedly, up to about 4000 MPa. It is also evident from this graph that in terms of energy consumption, CBN is the best choice for medium and rough machining of SCI.

### Cutting Temperature

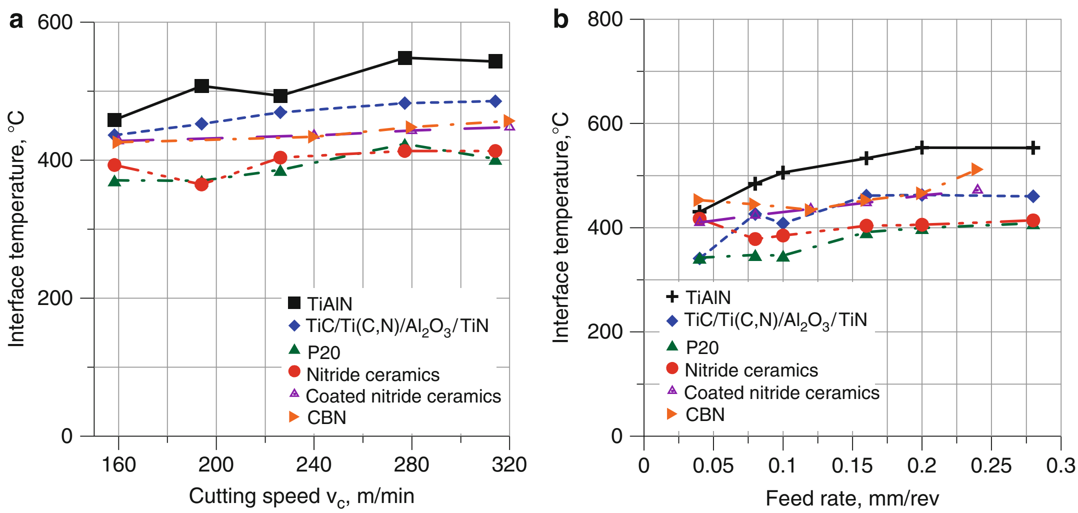
In thermal measurements a CCD (charge-coupled device)-infrared camera was applied to obtain a thermal map of tool-chip-work material system. The temperature measurement range was from 500 °C to 1000 °C, which corresponds to the CCD sensor capacity and the settings



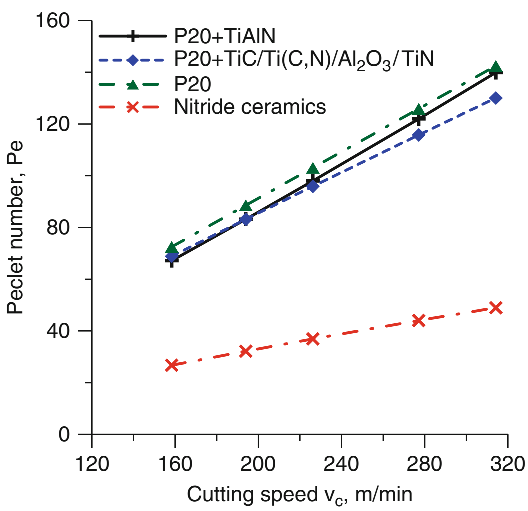

**Machining of Spheroidal Ductile Iron, Fig. 10** Thermal map for orthogonal cutting of SCI using CBN tool keeping: $v_c = 240$ m/min (**a**) and $v_c = 400$ m/min (**b**), f = 0.12 mm/rev, $a_p = 3.3$ mm. Own records presented also in (Grzesik et al. 2012)

(diaphragm position, infrared filters) used for the camera during the tests. This limit is fixed by the near-infrared wavelength (NIR) domain and the signal/noise ratio of electronic acquisition (3.4–5 μm wavelength interval). The observation area was 2 × 2 mm. The spatial resolution of the system is around 12 μm. The digital acquisition rate was two images per second. The calibration of the IR-CCD system was done against a black body cavity for which the temperature was carefully controlled with accuracy of ±1 °C. The operating temperature range was between 500 °C and 1000 °C. The characterization of the emissivity of the work material was made by heating the work material at various temperatures in a furnace with an inert gas so as to avoid any oxidation of steel. The thermal images registered for silicon nitride ceramic and CBN tools are presented in Figs. 9 and 10, respectively.

In general, during SCI machining the cutting temperature varies between 370 °C and 550 °C depending on the cutting tool material and cutting conditions applied, as shown in Fig. 11. In




**Machining of Spheroidal Ductile Iron, Fig. 11** Influence of cutting speed (**a**) and feed rate (**b**) on the cutting temperature. Cutting parameters: (**a**) P20, P20 + TiAlN, P20 + TiC/Ti(C,N)/$Al_2O_3$/TiN, $Si_3N_4$ – f = 0.16 mm/rev, $a_p$ = 2 mm, coated $Si_3N_4$ and CBN – f = 0.12 mm/rev, $a_p$ = 3.3 mm; (**b**) P20, P20 + TiAlN, P20 + TiC/Ti(C,N)/$Al_2O_3$/TiN, $Si_3N_4$ – $v_c$ = 280 m/min, $a_p$ = 2 mm, coated $Si_3N_4$ and CBN – $v_c$ = 240, m/min, $a_p$ = 3.3 mm




**Machining of Spheroidal Ductile Iron, Fig. 12** Influence of cutting speed on Péclet number. Cutting conditions: variable cutting speed of $v_c$ = 160–320-m/min, f = 0.16 mm/rev

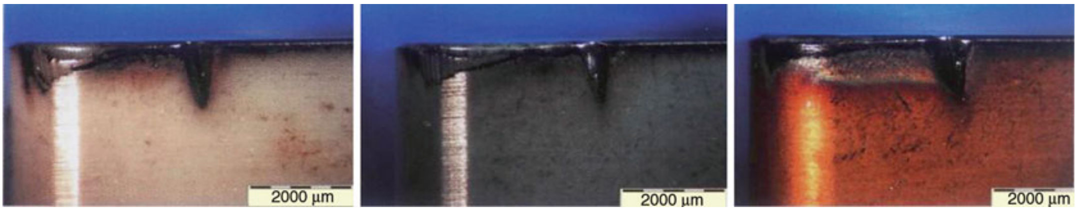
general, the contact temperatures are lower than in machining AISI 1045 carbon steel due to limited heat generation in the deformation source (mainly small discontinuous chips were formed). The lowest temperature, below 400 °C, was recorded for machining with uncoated silicon nitride ceramic tools (see Figs. 9 and 11). On the other hand, temperatures generated by CBN tools are about 50 °C higher, and the difference between maximum and average temperature depends on the cutting speed applied (for $v_c$ = 400 m/min, this difference is about 40 °C, as shown in Fig. 10b).

The differences in cutting temperature observed for various cutting tools can be explained in terms of the values of Péclet (Pe) number as shown in Fig. 12. In fact Pe number is visibly lower for silicon nitride ceramic tools for which the larger portion of heat can be transferred to the tool body. This is because the thermal conductivity of $Si_3N_3$ material at lower temperatures is high enough to cumulate more heat in the tool body.



## Tool Wear Phenomenon

Because SCI belongs to difficult-to-machine materials, it is important to characterize the wear performance of the tools recommended for practical use. At first sight, Fig. 13 illustrates how wear intensity changes when applying different grades of $Si_3N_4$-based ceramic tools. In particular,




**Machining of Spheroidal Ductile Iron, Fig. 13** Wear marks on uncoated and coated $Si_3N_4$ inserts (*left*, uncoated inserts with reference 100% tool life; *middle*, uncoated with modified microstructure with 170% tool life; *right*, coated SL654C grade with 240% tool life), after (Schneider and Richter 2006) with modifications

coating deposited on the $Si_3N_4$ substrate allows the increase of tool life by 240% (Schneider and Richter 2006).

A deeper insight at the wear behavior of different tools tested can be achieved by comparing wear curves which represent the changes $VB_B$ wear indicator versus time (or equivalently flank wear vs. cutting length) for different cutting speeds, as shown in Fig. 14. The flank wear width $VB_B$ was successively measured to achieve the end of tool life corresponding to the flank wear width $VB_B = 0.3$ mm using light optical microscope, and subsequently worn surfaces of the tool inserts were examined by means of a scanning microscope, model Hitachi S-3400 N, equipped with X-ray diffraction head EDS, model Thermo Noran System Six.

Due to the fact that silicon nitride is an electric isolator, the investigations were carried out in a low vacuum chamber keeping the vacuum pressure of 50 Pa. Both BSE (backscattered electrons) and ESED (environmental secondary electron detector) images were recorded. Wear products produced on the tool faces were analyzed using energy dispersive X-ray (EDX) technique.

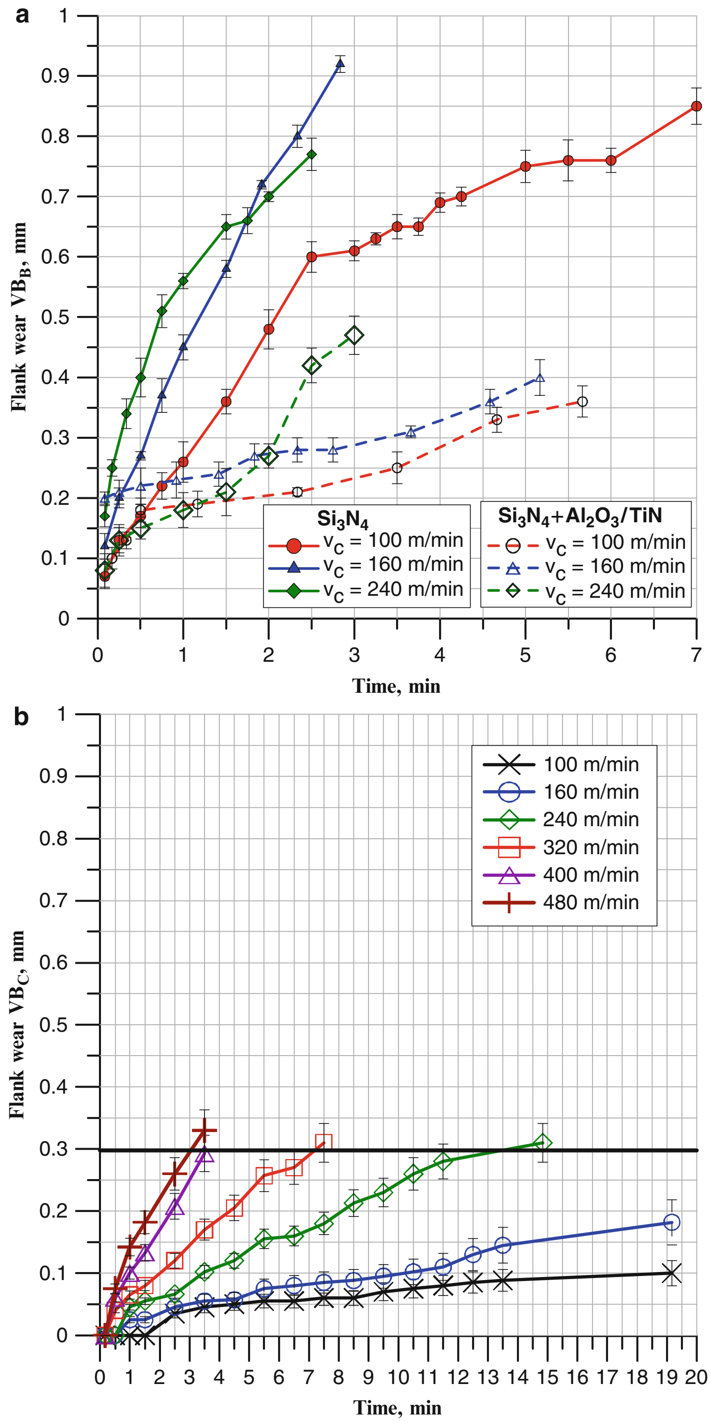
The wear tests confirmed substantially higher resistance of coated $Si_3N_4$ inserts (Fig. 14a) and CBN tools (Fig. 15b) to abrasive wear in comparison to uncoated tools. The practical findings of the wear tests are that in order to guarantee tool life of several minutes, the cutting speed should be kept at 240 m/min and 320 m/min for coated silicon nitride and CBN tools, respectively.

The wear patterns of worn tool surfaces assessed by means of appropriate SEM and BSE images are shown successively in Figs. 15 and 16. SME images shown in Fig. 15 confirm the wear evidence obtained by optical technique at macroscopic level shown in Fig. 14.

For $Si_3N_4$-based ceramic tools, wear results from two dominant wear mechanisms, i.e., abrasive and adhesive wear. In addition, oxidation wear locally occurs causing notch wear at the primary and secondary (trailing) cutting edges. In general, the nose wear is visually similar for uncoated and coated nitride ceramic tools, and geometrical features are comparable (Grzesik and Małecka 2011). A characteristic geometrical feature observed in these images is that the chamfer grooving extends up to the secondary cutting edge (Fig. 15a). As a result, the configuration of the nose changes, and small parts of the secondary cutting edge with local radius smoothen the workpiece surface similarly to micro-wiper tools (Grzesik and Żak 2009). EDS (energy dispersive spectroscopy) analysis performed in these parts of tool inserts revealed that built-up edges are formed on the rounded cutting edges due to intensive adhesive interaction between the insert and the workpiece material. The presence of BUE is supported by high content of Fe and Si in the EDS spectrum (Grzesik and Małecka 2011).

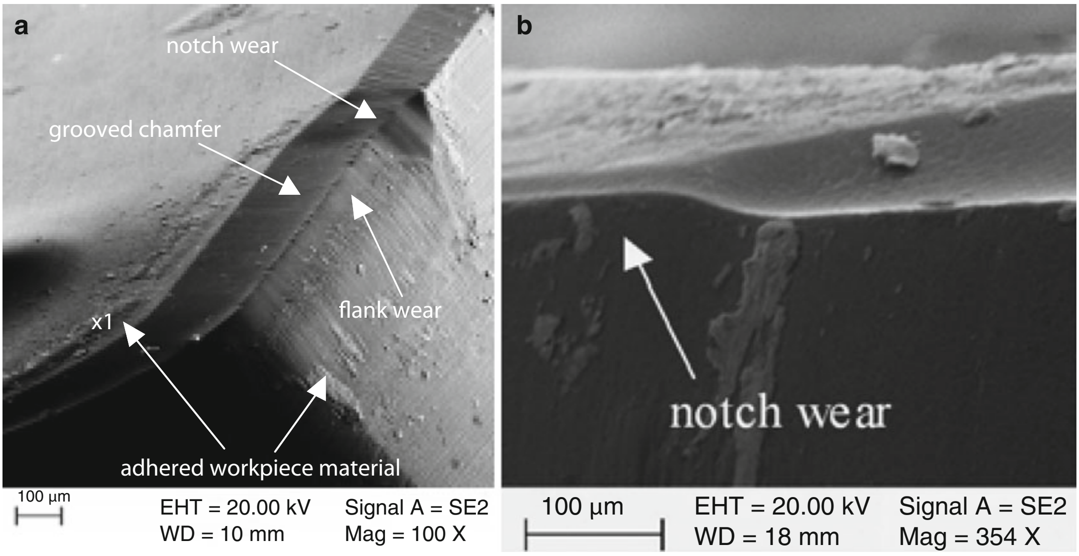
The second characteristic phenomenon in this area is that higher concentrations of iron and silicon occur, and it can be stated based on these data that in addition to abrasive and adhesive wear modes, also chemical wear (chemical dissolution) takes place under machining conditions employed. During the chemical analysis, the presence of oxygen was also revealed, which, in turn, may suggest the oxidation of wear products. On the other hand, a thermodynamically

**Machining of Spheroidal Ductile Iron,**
**Fig. 14** Wear curves showing wear indicator VBc versus machining time for feed f = 0.12 mm/rev. (**a**) Uncoated and coated $Si_3N_4$ ceramic, (**b**) CBN tools

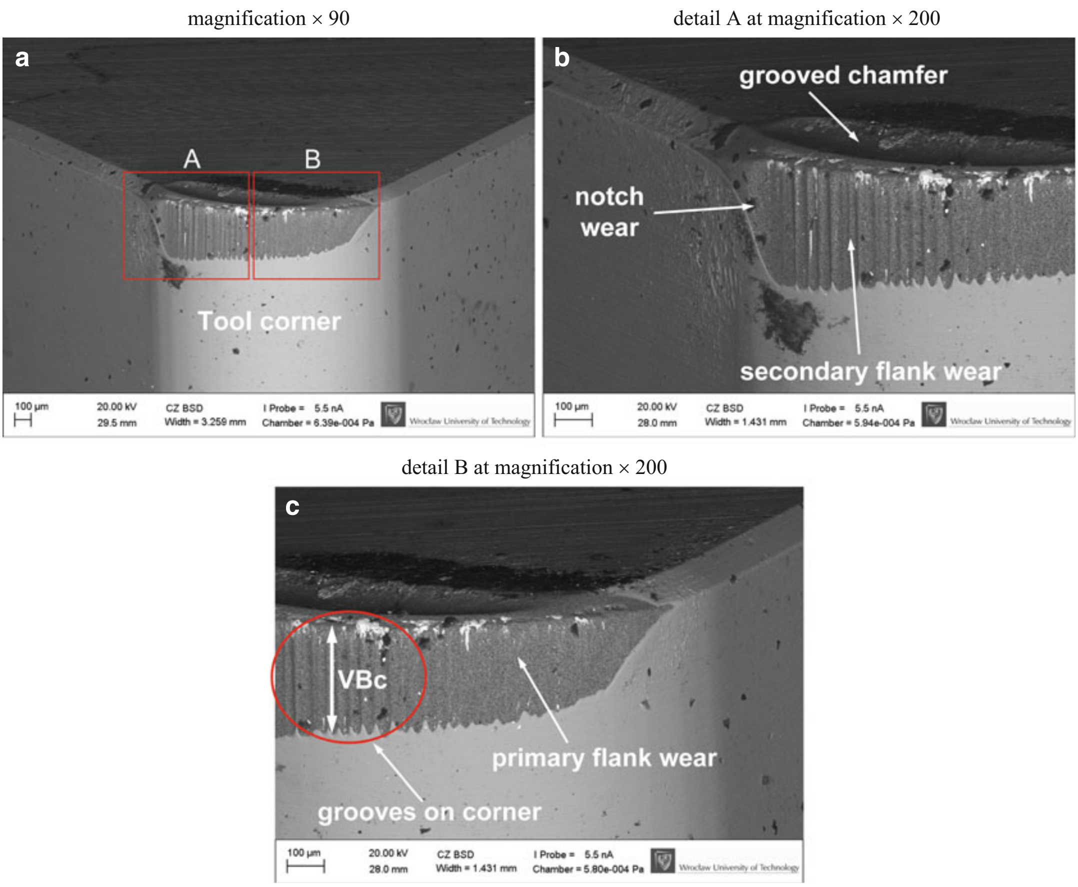




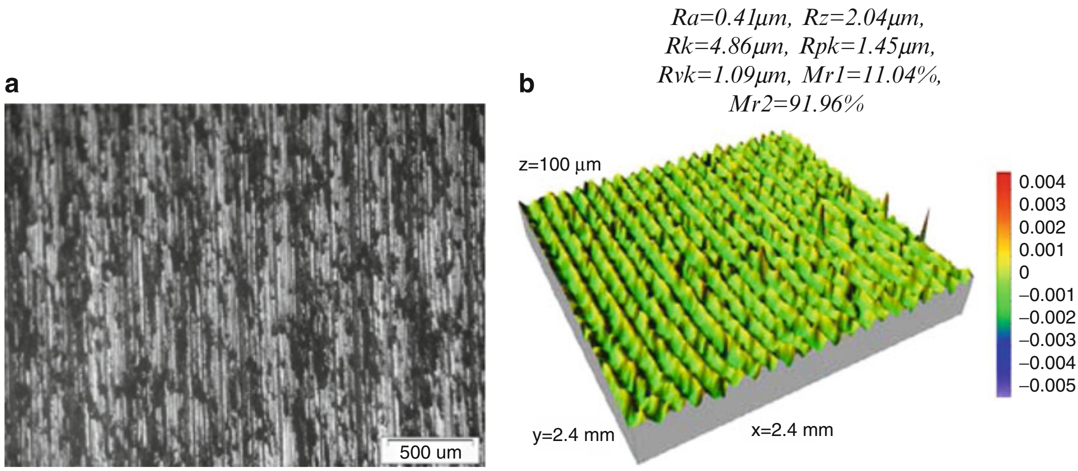

stable $Al_2O_3$ inner layer in the deposited coating acts as a diffusion barrier and causes the tool life to increase. Finally, three wear mechanisms, abrasive, adhesive, and oxidation, collectively govern the wear of uncoated and coated nitride ceramic tools.



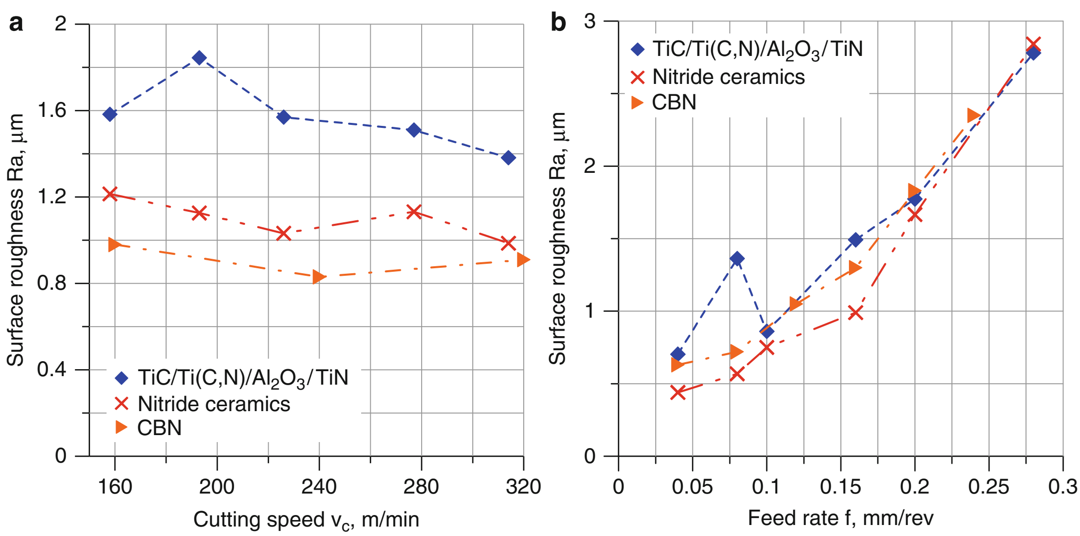

**Machining of Spheroidal Ductile Iron, Fig. 15** Worn primary (**a**) and secondary (**b**) cutting edges occurring for uncoated $Si_3N_4$ tool at $v_c = 240$ m/min. Own records presented also in (Grzesik and Małecka 2011)




**Machining of Spheroidal Ductile Iron, Fig. 16** Worn primary (**a**) and secondary (**b**) cutting edges occurring for CBN tool at $v_c = 400$ m/min and $f = 0.12$ mm/rev




**Machining of Spheroidal Ductile Iron, Fig. 17** Surface image showing characteristic lays at magnification 50× (**a**) and surface topography of surface machined by CBN tool keeping $v_c = 400$ m/min and $f = 0.08$ mm/rev (**b**) values of measured roughness parameters are specified above the surface




**Machining of Spheroidal Ductile Iron, Fig. 18** Influence of cutting speed (**a**) and feed rate (**b**) on the Ra roughness parameter. Cutting conditions: $v_c = 160–320$ m/min, $f = 0.16$ mm/rev (**a**) and $f = 0.04–0.28$ mm/rev, $v_c = 270$ m/min (**b**)

The possible geometrical wear modes observed during SCI machining with L-CBN (low CBN content) tools at cutting speed of 400 m/min are shown in Fig. 16. At higher cutting speeds, near 400 m/min, CBN tools do not suffer from notch wear at the primary cutting edge (Fig. 16c), but notch wear develops at the secondary cutting edge (Fig. 16b) similarly to nitride ceramic tools. Regarding the wear of flank face, regular patterns parallel to the workpiece movement are formed, whereas chamfer is visibly grooving. It also should be noted that the corner wear $VB_C$ is a representative wear indicator.

## Characteristics of Surface Finish

Characteristic surface topography and lays produced by turning operations of SCI are illustrated in Fig. 17. It is evident in Fig. 17a that graphite is smeared over the machined surface.

Surface topography presented in Fig. 17b confirms that CBN tools produce smooth surface with regular feed marks (only small, rarely distributed summits exist over the scanned surface).

The best surface finish in terms of Ra value was produced by CBN tools for which the Ra parameter varies between 0.8 μm and 1 μm depending on the cutting speed used, as depicted in Fig. 18a. For $Si_3N_4$ ceramic and multilayer coated carbide tools, Ra values were higher by about 20% and 60%, respectively. Keeping lower feed rates, as shown in Fig. 18b, and using $Si_3N_4$ ceramic and CBN tools, it is possible to obtain surfaces on SCI parts with Ra parameters even about 0.5 μm, as, for example, for feed rate of 0.04–0.08 mm/rev.

## Conclusions

Effective machining of spheroidal irons with mixed microstructures can be performed using coated silicon nitride ceramic and CBN tools. This is due to the fact that these cutting tool materials guarantee acceptable tool life at reasonably high cutting speeds up to 400 m/min.

Machining of CSI materials using both $Si_3N_4$-based ceramic and CBN tools is optimal in terms of energy consumption, especially for medium and rough machining operations.

Predominantly, $Si_3N_4$-based ceramic and CBN tools are worn by intensive abrasive wear of flank face and the chamfer. In addition, adhesive wear occurs. Moreover, oxidation wear locally occurs causing notch wear at the primary and secondary (trailing) cutting edges. The chamfer is intensively worn causing the formation of a groove along the active parts of the cutting edges and the corner.

It is possible to obtain good surface finish. For instance, surfaces with regular feed marks and the Ra of about 0.5 μm are generated by CBN tools.

## Cross-References

► Ceramic Cutting Tools
► Coated Tools
► Composite Materials
► Cutting, Fundamentals
► Wear Mechanisms

## References

Abele R, Sahm A, Schultz H (2002) Wear mechanism when machining compacted graphite iron. Ann CIRP 51(1):53–56

Boothroyd G, Knight WA (2006) Fundamentals of machining and machine tools. Marcel Dekker, New York

Byrne G, Dornfeld D, Denkena B (2003) Advancing cutting technology. Ann CIRP 52(2):483–507

CeramTec (2017) Coated SiAlON and silicon nitride cutting tool materials. www.ceramtec.com

CLAASguss (2006) Spheroidal cast iron EN-GJS (2006). www.claasguss.de

Graham D (2006) Machining cast iron. Manuf Eng 136(2):77–83

Grzesik W (2017) Advanced machining processes of metallic materials. Elsevier, Amsterdam

Grzesik W, Małecka J (2011) Documentation of tool wear progress in the machining of nodular ductile iron with silicon nitride-based ceramic tools. Ann CIRP 60(1): 121–124

Grzesik W, Żak K (2009) Mechanical, thermal and tribological aspects of the machining process of nodular cast iron with coated carbide and ceramic tools. Adv Manuf Sci Technol 33(1):31–43

Grzesik W, Rech J, Żak K, Claudin C (2009) Machining performance of pearlitic-ferritic nodular cast iron with coated carbide and silicon nitride ceramic tools. Int J Mach Tools Manuf 49:125–133

Grzesik W, Kiszka P, Kowalczyk D, Rech J, Claudin CH (2012) Machining of nodular cast iron (PF-NCI) using CBN tools. In: 5th CIRP conference on high performance cutting 2012, Zurich. Procedia CIRP, vol 1, p 500

Holmberg K, Matthews A (1994) Coating tribology- properties, techniques and applications in surface engineering, vol 28, tribology series. Elsevier, Amsterdam

Momper FJ (1998) Neue Schneidstoffe für neue Werkstoffe (New cutting tool materials for new workpiece materials). Werkstatt und Betrieb 131(5): 390–394

Nayyar V, Kaminski J, Kinnander A, Nyborg L (2012) An experimental investigation of machinability of graphitic cast iron grades; flake, compacted and spheroidal graphite iron in continuous machining operations. In: 5th CIRP conference on high performance cutting 2012, Zurich. Procedia CIRP, vol 1, pp 505–510

Sandvik Coromant (1999) Handbook of modern metal cutting. Sandvik Coromant Company, Stockholm

Schneider J, Richter G (2006) Eine Keramik für viele Fälle (One ceramics for many applications). Werkstatt und Betrieb 139(6):51–55

Schulz H, Reuter U (2001) Verschleißmechanismus geklärt: GGV-Motoren reif für die Großserie (Wear mechanism explains: engines made of GGV are suitable for large-lot production). Werkstatt und Betrieb 134(7–8):80–82

## Macro Geometry

► Cutting Edge Geometry

## Magnetic Bearing

Luis Uriarte
IK4-Tekniker, Eibar, Spain

### Abbreviations

| | |
|---|---|
| d.o.f | Degrees of freedom |
| FPGA | Field Programmable Gate Array |
| IGBT | Insulated Gate Bipolar Transistor |
| PWM | Pulse-Width Modulation |
| SMD | Surface-Mount Device |

### Synonyms

Electromagnetic bearing; Electromagnetically levitated spindle; Magnetic spindle

### Definition

Contactless bearing, in which the shaft is held in position by magnetic forces in the axial and radial directions (CIRP Dictionary of Production Engineering 2004).

### Theory and Application

#### Basic Working Principles

The idea of suspending an object with magnetism was first conceived in the mid-1800s. For a long time, considered complex, costly, and commercially ineffective, magnetically levitated bearings have lately proven their effectiveness, reliability, and competitiveness in industry, where the number of their applications is rapidly growing. Magnetic bearings show a number of important advantages over conventional bearing technologies, such as lubricant- and contamination-free operation, suitability for high-speed and high-performance applications, and inherently built-in instrumentation facilities for system monitoring. This development has, in parallel, also called for a high-performance motor drive technology. While magnetic bearings and motor drive technologies have been treated separately in the past, there is now a clear need for integration in order to achieve both technical and economic benefits.

#### Magnetic Bearing Components

A magnetic bearing has three major parts (see Fig. 1):

- Bearing actuators
- Position sensors
- Control system: controller and control algorithms

Figure 1 shows how a radial magnetic bearing works. There are two sensors that measure the X and Y position of the shaft relative to the fixed part. If the shaft goes to the right (moves in X+), the control increases the current in *coil x1* so that the force generated by the bearing is towards the left, putting back the rotor in the central position. Axial magnetic bearing works in the same way as the radial one; there is just some small difference in the geometrical design of the magnetic actuator.

The sensors are noncontact sensors that measure the distance between the rotor and the static part of the bearing, so that the control of the magnetic bearings can manage five degrees of freedom (d.o.f.) The sixth degrees of freedom (d.o.f.) is driven by the rotational motor.

The control system provides electric power to the bearings (see Fig. 2). This system consists of:

- Processor card with analogical inputs and outputs. This is the most important part of the system. Receives signals from the sensors and formulates bearing response based on control algorithm.
- Power amplifiers. Controls the current that is flowing in each bearing. Supplies each bearing

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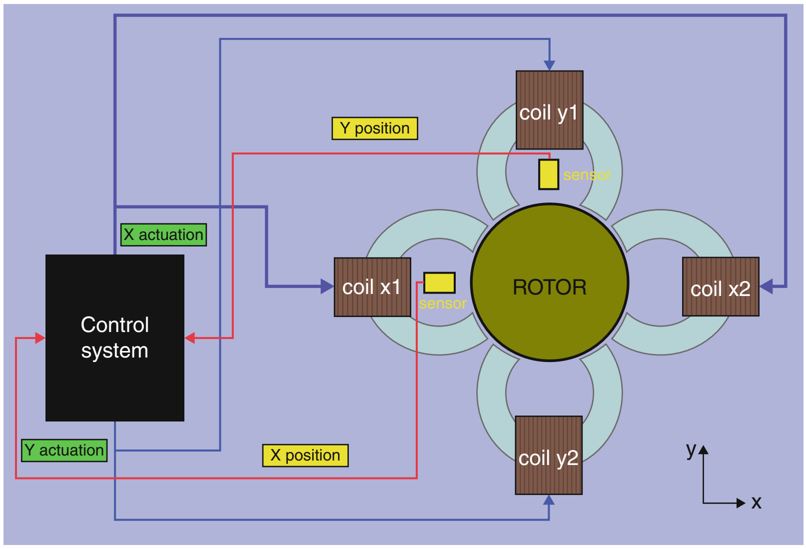
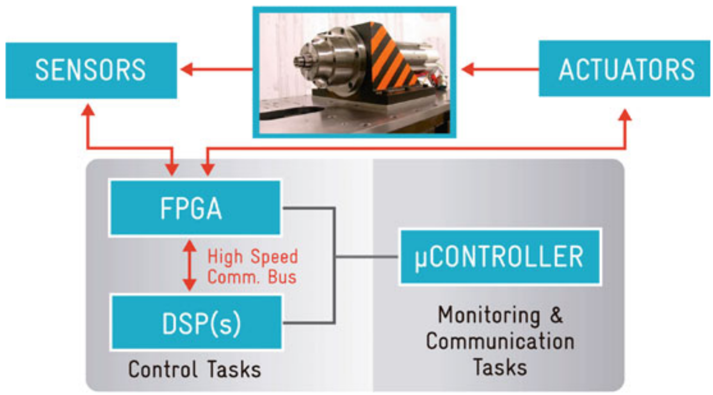



**Magnetic Bearing, Fig. 1** Radial magnetic bearing configuration




**Magnetic Bearing, Fig. 2** Electronics control system (bearings and motor). FPGA: Field Programmable Gate Array

the current solicited by the control. They are Pulse-Width Modulation (PWM) amplifiers. They provide/receive electrical power to/from the bearings.
- Power supply. Provides/receives and stores power to/from the amplifiers. The power supply, the power amplifiers, and the magnetic bearings convert electrical power in mechanical power and vice versa.

Digital control technology has proven to be the most suitable way to achieve the required system flexibility and reliability. This fact turns out to hold for the motor drive as well. Here, the latest developments in microprocessor and especially in digital signal processor (DSP) technology have paved the way for such integration, since these single-chip devices not only feature the needed computation power but, newly, also the peripherals and microcontroller capabilities necessary for field oriented Pulse-Width Modulation (PWM) motor drive control.

Apart from the advanced DSP technology, the latest achievements in power electronics allow integrating both magnetic bearing drivers and high-power switches for motor control in a very compact electronic circuit. Typically, such designs combine the highly compact and thermally optimal Surface-Mount Device (SMD) technology for bearing control with the latest Insulated Gate Bipolar Transistor (IGBT) technology for high-performance motor drive control, thus leading to a substantially raised level of power density and reliability.

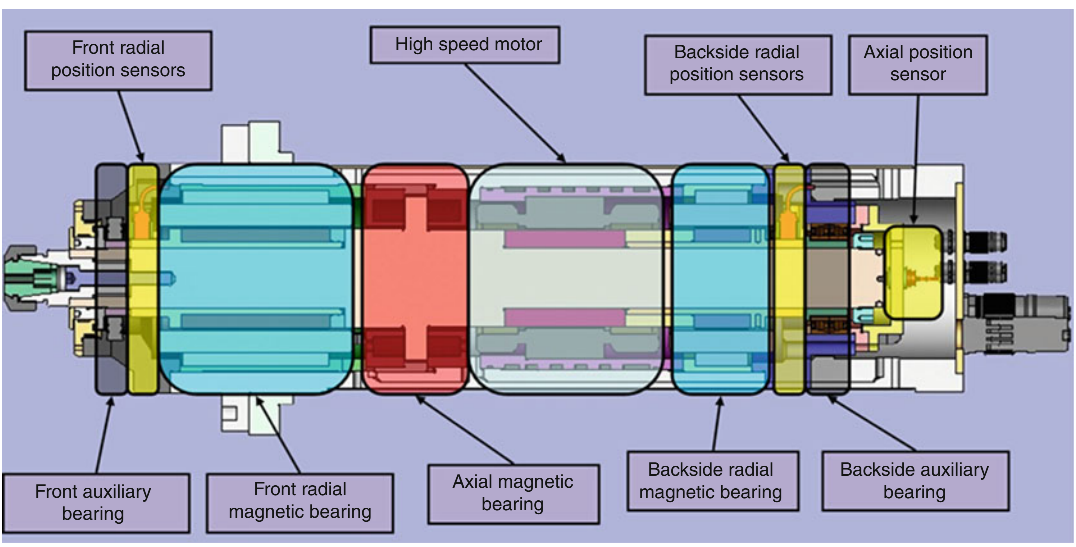
### High-Speed Spindle Application

Growing interest of industrial groups and research centers in the study and development of high-speed machining processes has been generalized. Aluminum machining industry is requesting high-speed and high-power spindles for the machining of large-volume workpieces. Ceramic bearings are the weak point of high-speed spindles. Their main drawback is that they are fragile, their life is limited, and the bearings replacement is a hard and expensive work in this kind of spindles. This is such a problem that some aluminum manufacturers have spare high-speed spindles to use as soon as one of the working spindles fails. In such way, that with a Total Cost of Ownership (TCO) strategy, the initial price of the spindle means only the 16% of the total cost for 24,000 h running (Abele et al. 2010).

This challenge has been mainly polarized towards the development of motors and rotating devices without mechanical contact between the rotating and static parts, controlling the rotor's position by means of magnetic forces. Magnetic bearings introduce some advantages to this kind of spindles, where they provide superior value compared to other types of bearings. Value is a function of the following: longer life, clean environment, extreme conditions, quieter operation, impact detection, and physical signal estimation (such as cutting forces and linear accelerations).

They have some drawbacks mainly that the spindle is bigger, since magnetic bearings need bigger volume for the same cutting force, and that the needed electric installation is also bigger. Product price could be another disadvantage for this kind of spindles, but as they are providing high reliability, long service intervals, and lower power consumption (due to frictionless bearings), the TCO (Total Cost of Ownership) should show better figures than ball-bearing high-speed spindles.

Apparently, high-speed machining should be an ideal application for magnetic spindles, with a conventional configuration (see Fig. 3). They are widely used in other fields of application such as semiconductor manufacturing, vacuum pumps, natural gas pipeline compression equipment, and energy storage flywheels (Coombs et al. 1999). However, the price, lack of damping, and reliability make the use of magnetic bearings in machining operations still reduced, and in practice, there are few experiences of magnetically levitated high-speed spindles.




**Magnetic Bearing, Fig. 3** Standard configuration of a fully magnetically levitated spindle

## Cross-References

▶ Bearing
▶ High Speed Cutting
▶ Spindle

## References

Abele E, Altintas Y, Brecher C (2010) Machine tool spindle units. CIRP Ann 59(2):781–802

CIRP Dictionary of Production Engineering (2004) Material removal processes, vol 2. Springer, Berlin

Coombs T, Campbell AM, Storey R, Weller R (1999) Superconducting magnetic bearings for energy storage flywheels. IEEE Trans Appl Supercond 9(2):968–971

# Magnetic Spindle

▶ Magnetic Bearing

# Main Spindle

▶ Spindle

# Maintenance

Franz Dietrich[1], Sebastian Thiede[2] and Günther Seliger[3]
[1]Institute of Machine Tools and Production Technology, TU Braunschweig, Braunschweig, Germany
[2]TU Braunschweig/IWF, Braunschweig, Germany
[3]Institut für Werkzeugmaschinen und Fabrikbetrieb Montagetechnik und Fabrikbetrieb, Technische Universität Berlin, Berlin, Germany

## Synonyms

### Definition

Maintenance subsumes a set of concepts, strategies, activities, and operations (Fig. 1), which, altogether, aim at the correction and/or prevention of failure or value degradation of technical systems. "Technical system" (or item) in this understanding refers to any part, component, device, subsystem, functional unit, equipment, or system that can be considered for maintenance individually. Failure is regarded as the termination of the ability of an item to execute an action or to provide a service as required.

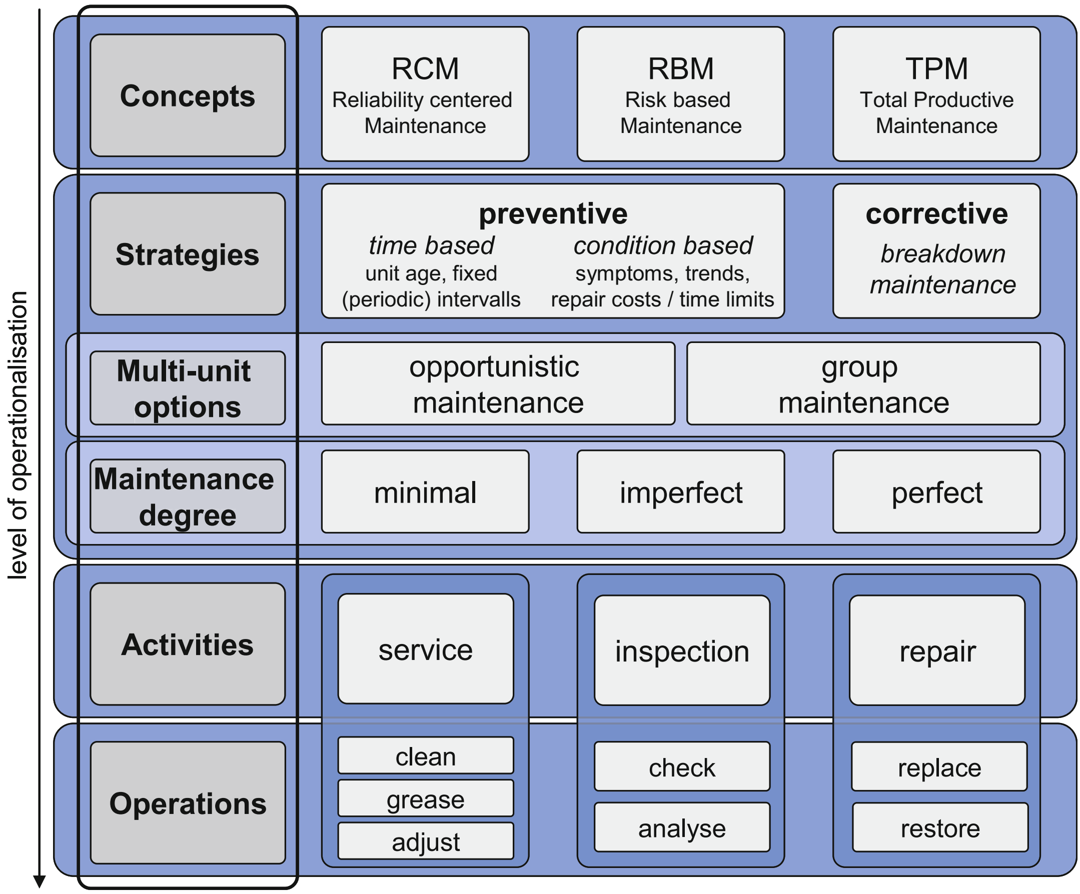
## Theory and Application

### Origins

Maintenance activities have been recorded as long as 5,000 years ago, as a part of inspection routines in the pyramids of Egypt. In the industrialized world, development of reliability engineering in the 1950s provided the fundamentals for sophisticated maintenance approaches. For example, purely corrective maintenance was enhanced towards preventive maintenance in the 1950. In the 1970, powerful diagnostics technologies emerged, which paved the road for condition-based maintenance and predictive maintenance. Today, a plethora of models to derive optimal strategies under boundary conditions, thorough literature about applications and widely accepted standards are available (Wang 2002; DIN 31051 2003).

### Theory

The aspects of maintenance should be viewed from different levels of abstraction, for which frameworks of maintenance terminology have been proposed (Fig. 1). Further reading can be found in Takata et al. (2004), Wang (2002), DIN 31051, and in EN 13306. The framework considered here distinguishes four major hierarchical layers of maintenance: concepts, strategies, activities, and operations. In the lowest two layers ("operations" and "activities"), maintenance actions (e.g., on a machine) are subsumed and classified in three major activities ("service," "inspection," "repair"). The strategy layer above this layer combines specific activities to accumulate strategies tailored to the specific object to be maintained (a system or its components). The strategy may be one of two fundamental types: corrective or preventive maintenance.



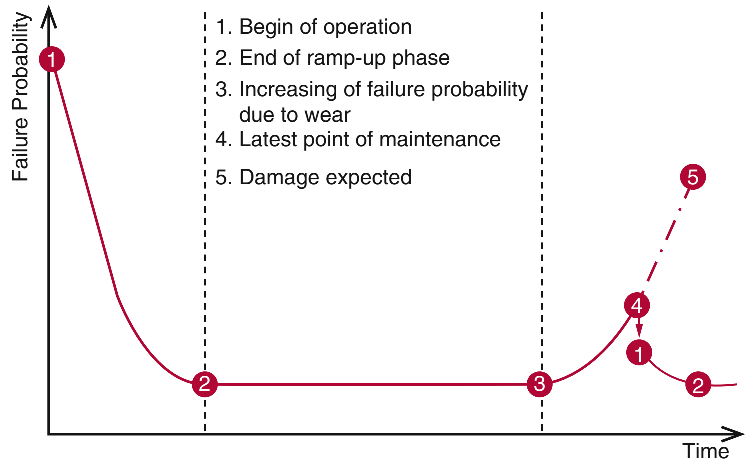

**Maintenance, Fig. 1** Hierarchical framework of maintenance terminology. (Takata et al. 2004; Wang 2002; DIN 31051 2003; Herrmann et al. 2007)

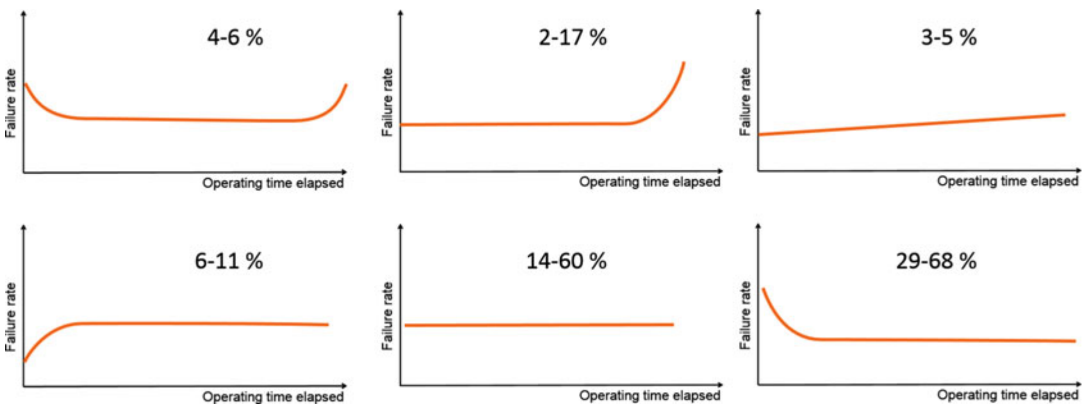
In corrective maintenance, repair activities are triggered by the occurrence of a failure, not earlier. In contrast, preventive maintenance tries to avoid failures before they occur (Mobley 2002). This requires earlier action, where scheduling of maintenance activities may be either time-based (system/component age or fixed schedule) or condition-based (based upon an evaluation of the component's actual wear progress) (Mobley 2002; Lanza et al. 2009; Gertsbakh 2006).

The top layer ("concepts") defines the top-level metrics for the evaluation of maintenance, in order to derive rules according to which maintenance strategies in the lower levels are selected. These metrics are synonymous to the targets to be achieved by maintenance, and common concepts are "Reliability Centered Maintenance" (RCM), "Risk Based Maintenance" (RBM), or "Total Productive Maintenance" (TPM). The top layer links maintenance to other domains of management and should be aligned with other lop-level company policies.

The appropriateness of a specific maintenance system for a given technical system is heavily dependent on the system's failure rate over operating time elapsed. The bathtub curve (Figs. 2 and 3 top left) is often referred to as an idealistic template of this function. It features three characteristics regions: in the early operating phase, an elevated failure rate due to production flaws is considered; in the main operating phase, stochastic failures cause a constant, low failure rate; in the late operating phase, wear and deterioration increase and cause elevated failure rates again. Typically, the Weibull function is employed to describe this model.

**Maintenance, Fig. 2** The bathtub curve, a model of failure rate vs. operating time elapsed



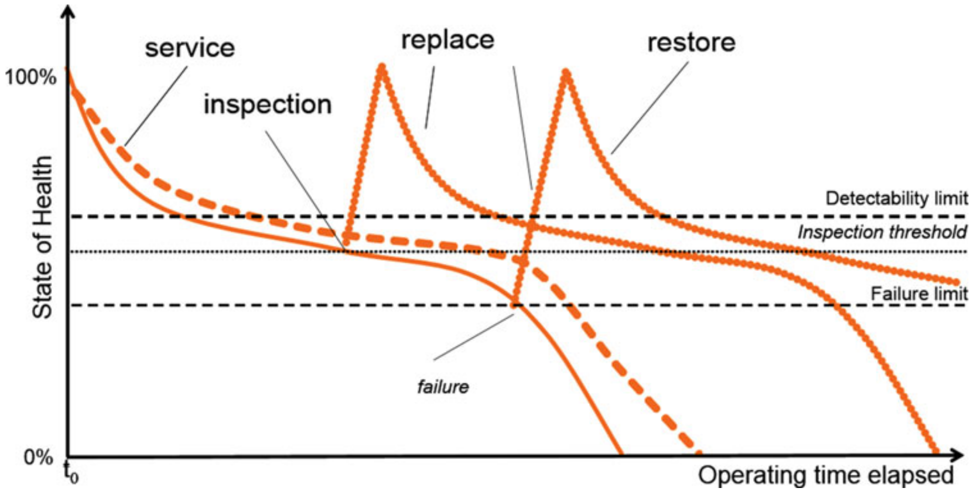

**Maintenance, Fig. 3** Typical progression of failure rates over time for different technical components (bathtub curve on upper left) (Bertsche and Lechner 2004)

However, studies show that there is only a minority of technical systems, for which all three regions of the bathtub curve can be recognized clearly. In the majority of applications, there is only a subset of the three regions obvious, so that, in order to simplify the parameterization in specific applications, five more types of functions that resemble the Weibull function partially are introduced additionally (Bertsche and Lechner 2004). Figure 3 shows these function prototypes (besides the bathtub curve on top left) and denotes the frequency of occurrence observed in a practical survey (Bertsche and Lechner 2004).

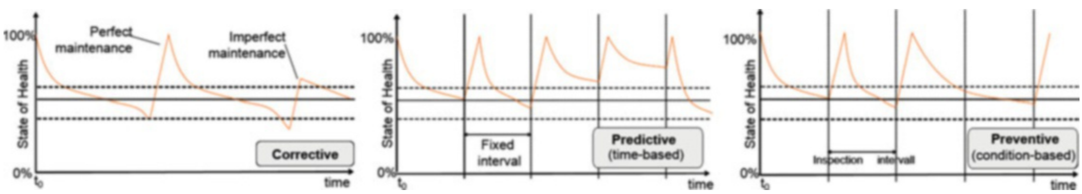
## Application

The integral of the failure rate function yields a measure of the depleted "state of health," i.e., the state of functional degradation of a system. Figure 3 sketches this depletion by deducting the integral of the Weibull function from the value 100% (full health of the system). In the early stage, functional degradation progresses fast; in the middle stage, degradation progresses slow; and, in the final stage, degradation progresses fast, again. It was discussed before that, in many applications, the Weibull function degrades, which, in consequence, causes that the S-shaped curve degrades and the affected regions become straightened (Takata et al. 2004).

Figure 4 depicts the effect of various maintenance activities. "Replacement" and "Restoration" mean literally that the curve is set (back) to a higher level. In the ideal case, this reset returns the state of health back to the initial value of




**Maintenance, Fig. 4** State of deterioration/state of health and triggers of maintenance actions (Takata et al. 2004)




**Maintenance, Fig. 5** Long-term effects of maintenance activities/strategies on deteriorating com-ponents (Takata et al. 2004)

100%. "Service" reduces the effects of wear, so that degradation becomes slower and operating time longer. "Inspection" evaluates the actual state of wear, so that violation of a predefined maintenance threshold can trigger appropriate preventive maintenance activities.

Figure 5 shows the fundamental effects and differences of corrective maintenance, time-based maintenance, and condition-based maintenance. It is noteworthy that corrective maintenance exploits the desired maximum operating time of the component and its maintenance intervals become long, but it implies high risk of unplanned failures and stoppages of the production. Preventive strategies involve periodic replacement or condition triggered activities, where the scheduling of maintenance activities can be aligned with other, regular downtimes. However, while enjoying the positive effect of less unplanned downtime due to "early" maintenance, one has to accept the compromise that the maximum achievable operating time of the maintained component is not exploited fully and that maintenance activities have to be scheduled more frequently.

In practice, it is not possible to propose one superior maintenance strategy – the application-specific influences and decisions are just too diverse. Most prominently, there are the specific progression patterns of functional degradation under the application-specific stresses and strains as well as the serviceability of the product (Takata et al. 2004). Furthermore, there are decisive economic variables which emerge from planned or unplanned production stoppages, maintenance staff, and material.

## Cross-References

- ▶ In-Process Inspection
- ▶ Life Cycle Cost
- ▶ Sensor (Machines)

## References

Bertsche B, Lechner G (2004) Zuverlässigkeit im Fahrzeug- und Maschinenbau (Reliability in Automotive and Machine Industry), in german
Birolini A (2004) Reliability engineering – theory and practice
DIN 31051 (2003) Grundlagen der Instandhaltung (Fundamentals of Maintenance), in german
EN 13306 (2010) European standard "maintenance terminology", Ref.Nr. EN 13306:2010 D/E/F
Gertsbakh I (2006) Reliability theory: with applications to preventive maintenance, corr. 2nd printing. Springer, Berlin
Herrmann C, Bergmann L, Thiede S (2007) An integrated approach for the evaluation of maintenance strategies to foster sustainability in manufacturing
Lanza G, Niggeschmidt S, Werner P (2009) Optimization of preventive maintenance and spare part provision for machine tools based on variable operational conditions. CIRP Ann 58(1):429–432
Mobley RK (2002) An introduction to predictive maintenance, 2nd edn. Butterworth-Heinemann, Amsterdam/New York
Takata S, Kimura F, van Houten FJAM, Westkämper E, Shpitalni M, Ceglarek D, Lee J (2004) Maintenance: changing role in life cycle management. CIRP Ann 53(2):643
Wang H (2002) A survey of maintenance policies of deteriorating systems. Eur J Oper Res 139:469–489

# Management of Production Enterprises

Wolfgang Boos[1] and Günther Schuh[2]
[1]Laboratory for Machine Tools and Production Engineering, Rheinisch-Westfälischen Technischen Hochschule Aachen, Aachen, Germany
[2]Forschungsinstitut für Rationalisierung (FIR) e. V, RWTH Aachen, Aachen, Germany

## Synonyms

Business management; Corporate management

## Definition

Within production enterprises the term management is used synonymously to the terms business management or corporate management. The term management can historically be derived from the Latin words *manum agere* ("lead by using the hands"). Typical management tasks of manufacturing companies are planning, organization, leadership, and controlling of the industrial value creation (Weatherly 2009).

## Theory and Application

### Introduction

Due to the high dynamics of today's economic environment production enterprises have to make quick and reliable decisions including all relevant corporate aspects. However, the enormous amount of information for the decision making is almost impossible to handle. It is therefore necessary to follow a strategy and to logically position an enterprise in the market. This article provides an overview over management processes and methodologies of production enterprises.

### History

The understanding of management and the demands in the management of production enterprises has changed considerably over time. However, management has always been indispensable in order to successfully accomplish a project. The Egyptian pyramids, for example, could have never been built without management tasks like planning, monitoring, or controlling.

There is broad consensus in literature that the modern management and its theory first emerged during the industrial revolution which started at the beginning of the nineteenth century in England from where it spread out to the European mainland and to North America. The foundation for the industrial revolution was primarily the steam engine designed by James Watt in 1765. But also new economic ideas such as *The Wealth of Nations* (1776) by Adam Smith supported the progress of industrialization. Smith used the example of a needle production to show that it was possible to enormously increase the productivity by specializing. Before the specialization one worker produced 20 units per day. Afterwards it was possible to manufacture 48,000 needles with ten workers daily. The reason for that increase was the higher skillfulness gained by repeating work steps and the possible machine usage (Robbins and Coulter 2004).

These technical and economic developments led to a drastic structural transition. Nonindustrial production in small businesses was replaced by industrial production in the soon emerging enterprises. The increasing size and complexity of those large enterprises increased the importance of the management since it had to coordinate the growing division of labor. As a result of the practical importance science began to deal with the management of production enterprises. In the late nineteenth century, the first business schools in German speaking countries were founded in Leipzig, Vienna, and St. Gallen. The management theory started to establish itself as an independent scientific discipline (Hungenberg and Wulf 2015).

## Regulatory Framework Production and Management

The regulatory framework of production and management is the basis for the management in modern production enterprises. It contains all relevant aspects of an enterprise and puts them into a general context. The framework is derived from the new St. Gallen management model (Rüegg-Stürm 2003).

The regulatory framework contains the internal aspects business structure, business development and business processes as well as the stakeholders as an interaction partner with the outside world and the environment as an external factor that affects the enterprise.

### Business Structure

The generic term "business structure" aggregates the company's constituent elements. They include the organizational structure, resources, information systems, and the culture. The *organizational structure* reflects the internal organization of the enterprise. *Resources* describe the operational input and production factors, which can either be tangible or intangible. The *information systems* support all further processes and are the basis for an efficient and effective operation. The *culture* relates to the normative management level, including the corporate culture, the corporate constitution, the corporate politics, and their interactions with the business development.

There are two different approaches of analyzing and structuring enterprises; process oriented and function oriented (Porter 1985). In an attempt to integrate the company's activities technically and organizationally, standalone subprocesses are bundled into process chains. Through this process-oriented organizational structure a higher flexibility regarding unplanned changes in the order fulfillment can be ensured.

The *process-oriented enterprise model* divides the process of creating value into subprocesses. It is thus possible to elucidate the consumption of resources by the principle of causation and support the identification of core processes.

In contrast the *function-oriented enterprise model* has its origin in the organizational structure. Based on the organizational job positions different units of the enterprise are regarded. Thus there is a focus on organizational subunits rather than on processes. In cost perspectives each subunit has to be optimized independently.



### Business Development

The essential requirements for the success of production enterprises are reactivity and flexibility in order to be able to adapt to market developments. Because of unpredictable changes in the future enterprises only have limited possibilities to design the basic conditions of their actions. Changes can result from new technologies, modified customer needs, governmental interventions, or competitor's behavior. Those changes are barely predictable and thus difficult to plan in the long-run. It is therefore necessary to ensure that enterprises are versatile to handle those unpredictable changes. Occurring market changes force the enterprises to adjust their processes and to adapt their market positioning. The realignment of an enterprise can be based on new purchasing conditions or capital supply as well as new competitors and changing customer requirements. The reasons for realignment can also be derived from the enterprise itself since rising and nonattributable shares of overhead costs as well as inefficient administration enormously reduce the competitiveness. They force the enterprise to realign the agility of the processes (Schuh et al. 1998).

The ability to quickly identify market developments and to immediately react to those changes is the key task of the business development.

Within the framework *Production and Management* the business development includes the strategy, the three modes of development called renovation, improvement, and operation as well as the controlling. It contains the corporate strategy up to the strategic management and the operational management. The three modes of development are influenced by the strategy. Thus the strategy has the task to not only keep the enterprises' performance (*operation*) but also to continuously improve *(improvement*) and if necessary to renovate it radically (*renovation*) (Rüegg-Stürm 2003). The controlling focuses on the target-performance comparison of the strategic targets. It is therefore a necessary basis for future decisions of the business management.

### Business Processes

All processes in an enterprise are called business processes. They are classified into technology management, innovation management, factory planning, production management, logistics management, quality management, purchasing management, service management, and technical sales (Schuh and Kampker 2011). Using resources, business processes are aiming at the transformation of input into process-specific output. The generated output of a business process is at once the input for following internal and external business processes. This connection leads to a customer-supplier relationship between the processes. Most business processes consist of both technology and corporate processes.

- Technology processes transform tangible input into tangible output
- Corporate processes transform intangible input into intangible output

Technology as well as corporate processes can be differentiated into management, planning, execution, and support processes.

### Stakeholders

An enterprise never exists for its own sake but always to generate social benefit. That is why it is located in an area of conflict between different stakeholders like investors, employees, customers, suppliers, the government, and the general public. The stakeholders are unified by the idea of preserving and successfully developing the enterprise although every stakeholder has specific demands which the management has to consider appropriately.

In the management theory stakeholders are groups or individuals who are affected by any form of value creation. All groups which could have an impact on the achievement of an enterprise or are affected by the impacts of the enterprises' activities are included. This perspective is extended by the stakeholder concept which was developed in the early 1960s at the Stanford Research Institute (USA). It covers not only the classic contract and market partners like suppliers, customers, employees, investors, managers, and the state, but also those stakeholders who do not have a formal or a market-law relationship or are even hostile to the enterprise (Freeman 1984).

Enterprises are understood as a political protagonist. The most common "social stakeholders" include among others: federations and interest lobbies of all kinds, political parties, international nongovernmental organizations (NGOs), citizens' initiatives, but also direct neighbors of the enterprise's location. Referring to those stakeholders it is obvious that these groups have many different and also contrary demands to the enterprise.

### Environment

The environment indicates relevant reference areas in the surrounding of an enterprise. The enterprise interacts with the elements of the environment and is dependent on their development and changes. Besides the direct effect on enterprises the environment also influences the stakeholders.

The environment includes the society, nature, technology, economy as well as norms and values. Whereas the *society* has the greatest influence on the other elements of the environment. It affects the ecological understanding (*nature*), influences the development of *technologies*, defines the *economic framework* and represents specific *norms and values* (Rüegg-Stürm 2003).

The environment is not only important in terms of ecological awareness of the society but also by building a framework of limited resources, climate, or access to the sea which has a direct impact on enterprises.

## Cross-References

- ▶ Information Management
- ▶ Knowledge Management
- ▶ Learning Organization
- ▶ Operations Management
- ▶ Planning
- ▶ Process
- ▶ Product Life Cycle Management
- ▶ Production
- ▶ Production Networks
- ▶ Supply Chain Management
- ▶ System

## References

Freeman RE (1984) Strategic management: a stakeholder approach. Financial Times Prentice Hall, Marshfield

Hungenberg H, Wulf T (2015) Grundlagen der Unternehmensführung [Fundamentals of corporate governance], 5th edn. Springer, Berlin. (in German)

Porter ME (1985) Competitive advantage: creating and sustaining superior performance. The Free Press, New York

Robbins SP, Coulter M (2004) Management. Prentice Hall India, London

Rüegg-Stürm J (2003) Das neue St. Galler management-Modell: Grundkategorien einer integrierten Managementlehre [The new St. Gallen management model: basic categories of an integrated management theory]. Haupt Verlag, Bern. (in German)

Schuh G, Kampker A (2011) Handbuch Produktion und management 1: Strategie und management produzierender Unternehmen [Manual of production and management 1: strategy and management of manufacturing companies]. Springer, Berlin. (in German)

Schuh G, Millarg K, Göransson Å (1998) Virtuelle Fabrik: Neue Marktchancen durch dynamische Netzwerke [Virtual factory: dynamic networks as a new market opportunity]. Hanser, München

Weatherly JN (2009) Handbuch systemisches management [Manual of systemic management]. Medizinisch Wissenschaftliche Verlagsgesellschaft, Berlin. (in German)

# Management of the Extended Enterprise

▶ Supply Chain Management

# Manipulating Industrial Robot

▶ Robot

# Man-Machine Cooperation

▶ Human-Machine Collaboration



# Manual Assembly

Terje K. Lien
Department of Mechanical and Industrial Engineering, NTNU – Norwegian University of Science and Technology, Trondheim, Norway

## Synonyms

Assembly; Assembly by hand

## Definition

Assembly in industrial contexts is the act of putting together components to form a product that consists of more than one part. Assembly is one of the essential elements in manufacturing systems since almost industrial products consist of several parts or component.

The Oxford dictionary defines assembly in the manufacturing context as "The action of fitting together the component parts of a machine or other object" (Oxford dictionary).

Manual assembly covers all operations where the main part of the operation is carried out manually. Some suboperations may be executed by machines like handheld electrical screwdrivers or similar. As long as the overall speed of operation is determined by then manual effort and the major part of all suboperations are manual, the whole assembly operation is classified as manual.

Single piece products do often need packaging which in a way is assembly, i.e., assembling the product and its wrapping. Although packaging strictly speaking is not assembly according to the formal definition, it is often seen as part of an assembly process.

## Theory and Application

### The Elements of Assembly

All assembly tasks consist of three or four basic subtask types:

- Identifying and gripping a part
- Bringing the part to the placement or insertion position
- Fitting or insertion
- Optionally securing the part

#### Identifying and Gripping Parts

The parts are normally stored in containers before assembly. Usually different component types are stored in separate containers so that identifying is not a big problem. In some cases, however, several types are mixed in a pile or in a container. Then identifying the correct part requires more attention. If the parts are very similar in shape and size, like many electronic components, there is need for clear marking of the containers for identification.

Gripping the part can present challenges for fast assembly. Components that are tightly packed in a container are difficult to grip and should be separated by some mechanical mean in the setup for the assembly operation preparation.

#### Move the Part for Placement

Basically, it is easy to bring the part to the correct placement position which is usually straightforward. However, in the case of manual assembly of electronic circuit boards, there are many similar positions where a part will fit. To guide positioning, there is normally a printed guide in the form of designation or numbering for each part on the circuit board. Additionally, a system where a light spot aids identification of the insertion position can be used. Then the sequence of insertion tasks is predefined, the identification of the part to pick is shown on a display, and the insertion point is illuminated on the board.

#### Placing or Insertion

When the part is properly brought to the place of insertion, it has to be placed or inserted properly. Some parts are simply stacked on top of the previously assembled parts. They will be secured by the parts that follow. In other cases, the part has to be inserted with very tight tolerances. The latter is the case with ball bearings and similar components. Additional jigs for alignment and tools for force application may be needed.

#### Securing the Part

Some parts require securing after placement. The securing is depending on requirements for tightness, force, and ease of disassembly. Several securing methods are available:

- Securing by snap devices integral in the parts. The securing is obtained as the part is pressed past the snap lock edges in the insertion phase.
- Securing by deformation of locking tabs. This is an old favorite for tinplate toys but is used in many products. The method requires a suitable tool for bending the tab properly for securing.
- Securing by screwing. This variant requires picking up the additional fastening device, a screw, a nut, or both. In addition, some screwing tool is required. This can actually be considered as an assembly subtask by itself.
- Securing by gluing. This method requires application of glue before placement of the part. Intermediate securing before the glue sets might be required.

- Securing by soldering. This is the method for all electronic assembly. In single unit or small batch production, each component may be soldered manually after insertion. This requires the use of a soldering tool and application of solder metal. For large batch production, the soldering is done in a separate soldering machine. In this case, all wire ends of the inserted parts have to be cut 2–3 mm from the board underside and bent to secure that they do not fall out in handling before the soldering machine.

### Assembly Workplace Layout

In small- and medium-sized product assembly, the workplace for assembly should be arranged in an ergonomically optimal way. This is beneficial for the assembly worker since it will minimize the physical strain during the working day. It will also provide the most efficient execution of the assembly tasks. Based on experience over long time certain elementary rules for good assembly, workplace layouts have been established. These rules are based on definition of movement classes for the assembly subtasks. Five classes are defined (Holt 1962):

- Class 1. Finger movements, i.e., movements of the fingers without moving the hand.
- Class 2. Finger and hand movements. These movements are done with the forearm stationary.
- Class 3. Finger, hand, and forearm movements. These movements are performed using the elbow as pivot.
- Class 4. Finger, hand, and complete arm movement. The upper body is nearly stationary.
- Class 5. Whole body movement without walking.

The movements in classes 1–4 are the normal movements in task where the worker sits at the worktable. In standing pose, all classes are possible. Continuous execution of class 5 movements is tiring and should be avoided.

For efficient work, the assembly subtasks should be of the lowest classes possible. But variation between the classes should also be sought as this eliminates tiredness and boredom and possible injury due to static loads on elbows or shoulders.

The layout of an assembly workplace should reflect this by placing the product to be assembled in a central area within class 3 reach of both arms. The use of jigs for stable support of the product is advised to relive one hand from static holding loads.

All components should be placed in containers within the range of class 3 reach for the most frequently used components; less frequently used components should be placed within the range of class 4 movements.

It is also advantageous to divide the tasks evenly between the left and right hand. By a rhythmic distribution of the movements, fast and reliable assembly is obtainable.

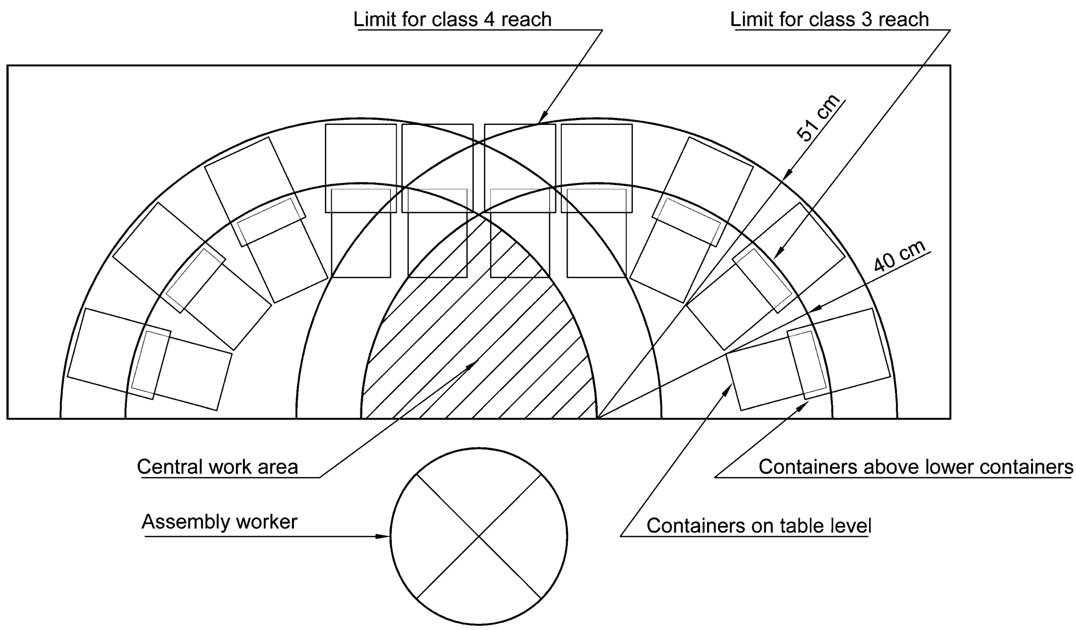
Figure 1 shows a recommended layout for light product assembly. The dimensions for class 3 and 4 movements are valid for average male workers. The tools like power screwdrivers and similar should be suspended from above in counterweight or spring suspension systems. Less frequently used small tools should be placed in the class 3 area as close to the central work area as possible.

### Planning Assembly Operations

For greatest assembly efficiency, all operations in the assembly process should be well planned to avoid unnecessary movements and time consumption. There are several tools available for this purpose: process charts that are used for process-level studies, motion studies, and time studies used for operation-level planning.

#### Process-Level Planning

The process chart is used to survey the transport routes and handling tasks between the assembly operations and the work content and time consumption for a standard execution of each assembly operation. This enables balancing the process to get the highest possible utilization of each workstation. The distance of movement and mass of transported parts between the operations is also recorded. By studying the possible routing variants, the volume of components flowing into the assembly process, and the methods for




**Manual Assembly, Fig. 1** Recommended worktable layout for light to medium assembly work (Adapted from Holt 1962)

component transport, the maximum efficiency assembly process can be selected (Riggs 1987).

### Operation-Level Planning

At each workplace, the manual assembly subtasks can be studied by operation method studies. Normally there is a distinction between motion study and time study. In these studies, the layout of the workplace is analyzed; the placement of the components to assemble is described. The motion study concentrates on recording and analyzing the motion element types and magnitude of motions. The optimization goal is minimizing movement. The time study is used to determine the normal (average) time consumption for optimized movements (Holt 1962; Riggs 1987).

In particular for manual assembly or similar repetitive task, there exist very detailed planning methods. These use what is called synthetic times. Synthetic time is the name for movement time data that are synthesized for time studies in many different companies for different tasks. The standard time represents what is considered normal performance of a healthy adult worker performing at normal pace. The most well-known synthetic time system is the MTM system. MTM stands for methods-time measurement. This system was developed in the spirit of scientific management; it assumes that there is always a best way of performing standard manual operations that occur frequently in manufacturing and assembly. These manual operations are broken down into standard movement element like reach, grasp, move position, and similar. Furthermore, the distance of movement, the weight of the handled object, the precision at grasping and positioning, and the effect of simultaneous operation of two hands are considered. The time required for executing the different handling subtasks is described in tables. A standard tabular system for calculation of a complete cycle time base exists; it enables trained people to quickly calculate estimated standard times for light and medium handling tasks in industry (Maynard et al. 1944).

Synthetic time systems like the MTM system should be used with care. They assume optimal conditions and do not include time for the operators' personal needs. Nor do they consider any stops that are the result of unexpected stops due to machine breakdown, material supply errors, or similar. These factors must be included in the total planning of operations to obtain reliable planning data.

### Manual Assembly and Automation

The constant strive for higher efficiency and lower costs is a main driver toward automation. In the field of assembly, there are however many obstacles for automation. The complexity of assembly, the need for human fingertip feeling, and the ability to adjust to small variations in the components to assemble are typical challenges for automation. For this reason, many assembly systems combine some automatic operations with manual work on the more challenging tasks.

The assembly of cars was one of the first areas where manual work was combined with automation. The transport of the car was mechanical at a constant pace, while virtually all real assembly tasks were manual. This leads to high overall efficiency in the assembly process. The negative side effect was the hard pacing of the workers on the line. This negative aspect has been criticized since the introduction of mechanical assembly lines in the Ford Motor Company at the Highland Park Ford Plant in 1913. Since then much time has been spent on making the manual assembly task more benign to humans on similar lines. It is very difficult to avoid pacing by the mechanical conveyor on standard assembly lines. Therefore, alternative solutions are sought. One way is to decouple the automatic assembly system from the manual part. Where products start with a relatively simple basic structure which then is competed by more complex task, it is possible to have an automatic system to produce these simple basic structures. These are then fed to a manual section for completion. The manual completion can be organized in a way that allows the workers to set the pace, not the machines. Such systems have shown good productivity since they combine the efficiency of automatic operations where that is possible, with the flexibility of manual assembly where that is needed (Lien and Rasch 2001).

Automation of assembly operations has gone too far in some cases. The efficiency and stability of automatic assembly do not always live up to expectations. In these cases, companies take steps back and reintroduce manual assembly to obtain more stable and efficient assembly. This is particularly the case where companies have to handle decreasing lot sizes and increasing product variety (Bley et al. 2004).

Robotic assistance of manual assembly is another approach to automation. In this approach, robots or manipulators are used to augment the performance of humans in assembly. The robots can serve as tools for lifting, moving, and positioning heavy objects, while the operator takes care of the more delicate tasks that require human dexterity and fingertip feeling. This is advantageous since it reduces the physical burden of the operator, and at the same time, the speed of assembly will usually increase. Another presenting task is to use automatic feeders to present parts for manual assembly. Again, it is machines that perform a standardized task, while the human operator finishes the tasks where human capabilities are utilized at their best (Krüger et al. 2009).

## Cross-References

▶ Assembly
▶ Assembly Automation
▶ Feeding
▶ Handling
▶ Manufacturing System
▶ Material Flow

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## References

Bley H, Reinhart G, Seliger G, Bernardi M, Korne T (2004) Appropriate human involvement in assembly and disassembly. CIRP Ann Manuf Technol 53(2):487–510

Holt K (1962) Bedriftslære (Science of industrial management). Aschehoug, Oslo

Krüger J, Lien TK, Verl A (2009) Cooperation of human and machines in assembly lines. CIRP Ann Manuf Technol 58(2):628–646

Lien TK, Rasch FO (2001) Hybrid automatic-manual assembly systems. CIRP Ann Manuf Technol 50(1):21–24

Maynard HB, Stegmerten GJ, Schwab JL (1944) Methods-time measurement. McGraw- Hill, New York

Oxford dictionary online. http://www.oxforddictionaries.com/definition/english/assembly. Accessed 25 Jan 2016

Riggs JL (1987) Production systems: planning, analysis, and control, 4th edn. Wiley, New York

# Manufacturing

Tiziana Segreto[1,2] and Roberto Teti[1,2]
[1]Department of Chemical, Materials and Industrial Production Engineering (DICMAPI), University of Naples Federico II, Naples, Italy
[2]Fraunhofer Joint Laboratory of Excellence on Advanced Production Technology (Fh J_LEAPT), Naples, Italy

## Synonyms

Fabrication; Production

## Definition

The entirety of interrelated economic, technological, and organizational measures directly connected with the processing/machining of materials, i.e., all functions and activities directly contributing to the making of goods.

Note: "Manufacturing" is often used synonymously for "production." However, its conceptual content is larger than that of "production," since it also encompasses managerial functions. Manufacturing is part of the supply chain between suppliers and customers of a manufacturing company. It includes the value adding processes, namely, fabrication and assembly, as well as the organizational functions, namely, process planning and production planning and control. Fabrication and assembly together are called production (CIRP Dictionary of Production Engineering 2004).

## Theory and Application

### History

The history of manufacturing begins with the world itself. The term "manufacture" is derived from two Latin words *manu* (by hand) and *facere* (make); the combination means "to make by hand" (Kalpakjian and Schmid 2002). Manufacturing began around 5,000–4,000 BC with the fabrication of various articles of wood, ceramics, stone, and metal. From ancient times until the eighteenth century, industry was practiced first within the family, based on slaves work (e.g., Greece, Rome) or as temple activities (e.g., Egypt) and later also as organized commercial enterprises of limited production capacity. In the East, industry prospered in the field of fabrics, dyeing, and jewellery; whereas in the West, industry started at the time of the Carolingians with the birth of the most powerful industries: iron and steel (first blast furnaces), weaving, papermaking, etc. In the seventeenth century, the consolidation of national monarchies and the consequent formation of larger nationwide markets, the development of transports and banks, yielded favorable conditions to the development of industry. In the second half of the eighteenth century, the *First Industrial Revolution* (1760–1830) marked the change from an economy based on agriculture and handicraft to one based on industry and manufacturing. The change began in England, where a series of machines were invented and steam power replaced water, wind, and animal power. However, the revolution eventually spread to other European countries and to North America. While England was leading the industrial revolution, an important concept was being introduced by Eli Whitney (1765–1825) in the United States: interchangeable parts manufacture. This would become a prerequisite for mass production. The mid- and late 1800s witnessed the expansion of railroads, steam-powered ships, and other machines that created a growing need for iron and steel. New steel production methods were developed to meet this demand. Also during this period, several consumer products were developed, including the sewing machine, bicycle, and automobile. In order to meet the mass demand for these products, more efficient production methods were required. Some historians identify developments during this period as the *Second Industrial Revolution*, characterized in terms of its effects on manufacturing systems by the following: (1) mass production, (2) scientific management movement, (3) assembly lines, and (4) electrification of factories.

Henry Ford (1863–1947) introduced the *assembly line* in 1913 at his Highland Park plant. The assembly line made possible the mass production of complex consumer products. In 1881, the first electric power-generating station was built in New York City, and soon electric motors were being used as a power source to operate factory machinery. This was a far more convenient power delivery system than steam engines, which required overhead belts to distribute power to the machines. By 1920, electricity had overtaken steam as the principal power source in the factories of the twentieth century, a time of more technological advances than in all other centuries combined (Groover 2007). From the mid-1950s up to the introduction of the first personal computer in 1981, manufacturing started turning digital, thus marking the initiation of the *Third Industrial Revolution*. Mechanical and electronic technologies changed to digital with the wide adoption in manufacturing of computers and information and communication technology (ICT), leading to the introduction of automated machines, systems, and processes in manufacturing (e.g., computer numerical control (CNC), computer-aided process planning (CAPP), just in-time production (JIT), cellular manufacturing, flexible manufacturing systems (FMS), etc.).

To date, manufacturing covers approximately 21 % of the EU's GDP providing more than 30 million jobs in 230.000 enterprises and is facing an intense and growing competitive pressure in global markets. The guidelines for the revitalization of the manufacturing industry pass through innovation of production processes and systems towards more efficient and smart solutions in terms of costs, quality of work, and increased competitiveness through research and development in the technological know-how. By the end of the twentieth century, industries have invested in the relocation of resources to increase competitiveness and reduce costs. Today, Europe has become aware of the importance of innovation in industrial production setting the goal to achieve, by 2020, 20 % of the GDP's manufacturing. This means investing heavily in the review of manufacturing processes and systems and therefore in automation.

In this framework, an ongoing paradigm shift in manufacturing points toward global production networks adopting new computing and Internet-based technologies as key enabling technologies to meet new challenges. This represents the *Fourth Industrial Revolution* that someone has recently called "Industry 4.0," leading to the flexible usage of diverse globally distributed, scalable, and service-oriented manufacturing resources.

To realize the full-scale sharing, free circulation, and transaction as well as on-demand use of manufacturing resources and capabilities in advanced production industries, cloud manufacturing (CMfg) has been proposed as a new service-oriented manufacturing approach. CMfg can be defined as an integrated cyber-physical system (CPS) that can provide on-demand manufacturing services digitally and physically for optimal resource utilization. It has been conceived as an extension of the cloud computing (CC) paradigm to the manufacturing sector. Compared with CC, the services managed in CMfg include not only computational and software tools but also various digital and physical manufacturing resources that different users in an industrial environment can remotely access on a shared basis (Gao et al. 2015).

The timeline of the four successive industrial revolutions is reported in Fig. 1.

## Manufacturing Activities

Manufacturing can be defined as the application of physical and chemical processes to modify the properties of a given start material in terms of its form, shape, size, mechanical characteristics, external appearance, etc., in order to fabricate a single part representing a product or multiple parts to be assembled to form a complex product. In order to perform a manufacturing process, it is necessary to utilize appropriated machines, tools, fixtures, energy, and manpower (Fig. 2).

Manufacturing is generally a complex activity involving people who have a broad range of disciplines and skills, together with a wide variety of machinery, equipment, and tools with various levels of automation, including computers, robots, and material-handling equipment.

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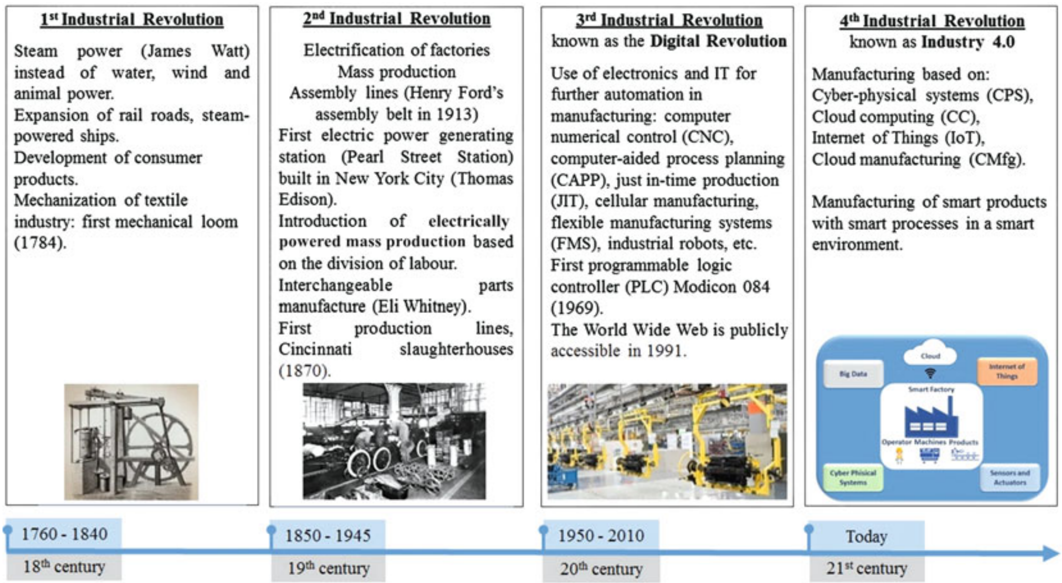
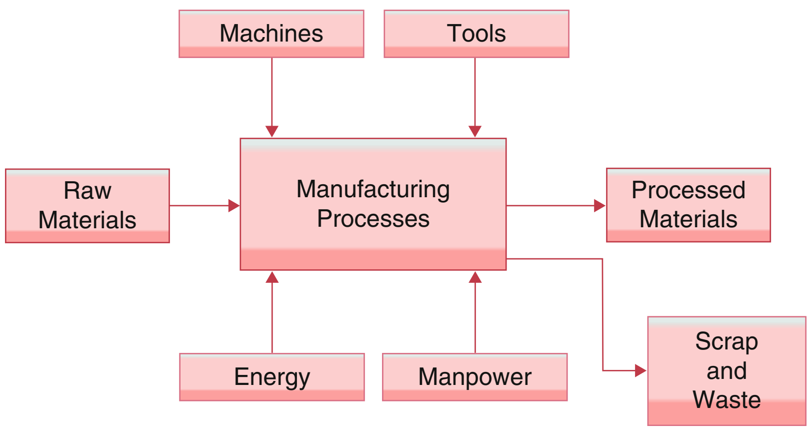



**Manufacturing, Fig. 1** Timeline of the four successive industrial revolutions




**Manufacturing, Fig. 2** Definition of manufacturing as a technological process

Manufacturing activities must be responsive to several demands and trends:

1. A product must fully meet *design requirements* and *specifications* and *standards*.
2. A product must be manufactured by the most *economical* and *environmental friendly* methods.
3. *Quality* must be built into product at each stage, from design to assembly, rather than relying on quality testing after the product is made.
4. In a highly competitive environment, production methods must be sufficiently *flexible* to respond to changing market demands, types of products, production rates, production quantities, and to provide on-time delivery to the customer.
5. New developments in materials, *production methods*, and *computer integration* of both technological and managerial activities in a manufacturing organization must constantly be evaluated with respect to their timely and economic implementation.

6. Manufacturing activities must be viewed as a large *system* in which all individual components are interrelated. Such systems can now be modeled in order to study the effects of various factors, such as changes in market demands, product design, costs, and production methods, on product quality and costs.
7. The manufacturer must work with the customer to get timely feedback for *continuous product improvement*.
8. The manufacturing organization must constantly strive for higher *productivity*, defined as the optimum use of all its resources: materials, machines, energy, capital, labor, and technology. Output per employee per hour in all phases must be maximized.

### Innovative Manufacturing Applications

Over the last 5 years (2010–15), the main addressed manufacturing issues have been:

- Manufacturing systems design, modeling, simulation and optimization
- Production planning, scheduling, and control
- Intelligent manufacturing (evolutionary algorithms, multi-agents, genetic algorithms, knowledge management, data mining, decision-making) (Ueda et al. 2009; Tolio et al. 2010)
- Virtual and augmented reality for manufacturing
- Supply chains and production networks (Váncza et al. 2011)
- Reconfigurable, flexible, and changeable manufacturing systems
- Globalization, scalability, and capacity planning (Putnik et al. 2013)
- Complexity manufacturing (ElMaraghy et al. 2012)
- Business models, strategic enterprise planning for change
- Energy and resource efficient manufacturing
- Sustainable and green manufacturing (Ueda et al. 2009)
- Advanced IT for manufacturing (virtual factory, cloud manufacturing, cyber-physical systems, Internet of things, Industry 4.0) (Gao et al. 2015)
- Maintenance strategies
- Process planning and control
- Mass customization and personalization
- Customer driven products/production (Tolio et al. 2010)
- X-to-Order (engineering, design, manufacture, logistics)
- Production quality (Colledani et al. 2014)
- Sensors and sensing techniques for zero defect manufacturing
- Logistics systems
- Inventory management
- Industrial product-service systems
- Additive manufacturing
- Bio-manufacturing
- Nano and micro manufacturing
- Human factors in manufacturing
- Learning factories and manufacturing education

## Cross-References

▶ Assembly
▶ Assembly Automation
▶ Assembly Line
▶ Design Methodology
▶ Production

## References

CIRP Dictionary of Production Engineering (2004) Manufacturing systems, vol 3. Springer, Berlin

Colledani M, Tolio T, Fischer A, Iung B, Lanza G, Schmitt R, Váncza J (2014) Design and management of manufacturing systems for production quality. CIRP Ann Manuf Technol 63(2):773–796

ElMaraghy W, ElMaraghy HA, Tomiyama T, Monostori L (2012) Complexity in engineering design and manufacturing. CIRP Ann Manuf Technol 61(2):793–814

Gao R, Wang L, Teti R, Dornfeld D, Kumara S, Mori M, Helu M (2015) Cloud-enabled prognosis for manufacturing. CIRP Ann Manuf Technol 64(2):749–772

Groover MP (2007) Fundamentals of modern manufacturing: materials, processes, and systems. Wiley, Hoboken

Kalpakjian S, Schmid SR (2002) Manufacturing processes for engineering materials, 4th edn. Pearson, Upper Saddle River

Putnik G, Sluga A, ElMaraghy H, Teti R, Koren Y, Tolio T, Hon B (2013) A scalability in manufacturing systems design and operation: state-of-the-art and future

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developments roadmap. CIRP Ann Manuf Technol 62(2):751–774
Tolio T, Ceglarek D, ElMaraghy HA, Fischer A, Hu SJ, Laperrière L, Newman ST, Váncza J (2010) SPECIES: co-evolution of products, processes and production systems. CIRP Ann Manuf Technol 59(2):672–693
Ueda K, Takenaka T, Vancza J, Monostori L (2009) Value creation and decision-making in sustainable society. CIRP Ann Manuf Technol 58(2):681–700
Váncza J, Monostori L, Lutters D, Kumara S, Tseng M, Valckenaers P, Van Brussel H (2011) Cooperative and responsive manufacturing enterprises. CIRP Ann Manuf Technol 60(2):797–820

## Manufacturing by Material Removal

► Cutting, Fundamentals

## Manufacturing Plant

► Factory

## Manufacturing System

Alessandra Caggiano
Department of Industrial Engineering, Fraunhofer Joint Laboratory of Excellence on Advanced Production Technology (Fh-J_LEAPT Naples), University of Naples Federico II, Naples, Italy

### Synonyms

Production System

### Definition

An organization in the manufacturing industry for the creation of production. In the mechanical and electrical engineering industries, a manufacturing system, in general, has an integrated group of functions, e.g., the sales, design, production, and shipping functions. A research function may provide a service to one or more of the other functions.

Note: Despite the conceptual difference between "production" and "manufacturing," in English usage, the term "manufacturing system" addresses a complete enterprise or a group of enterprises, an individual production department (e.g., foundry, turnery), or even a single work station (CIRP Dictionary of Production Engineering 2004).

#### Extended Definition

A manufacturing system can be defined as a combination of humans, machinery, and equipment that are bound by a common material and information flow. The input material flow consists of raw materials and energy, while the input information is related to the customer demand for the system's products. The outputs of a manufacturing system can likewise be divided into materials, such as finished goods and scrap, and information, such as measures of system performance (Chryssolouris 2006).

### Theory and Application

#### Introduction

According to the definition given in the CIRP Dictionary of Production Engineering, manufacturing systems are wide systems involving people, equipment, and procedures organized to accomplish the manufacturing operations of a company. Manufacturing systems include not only the groups of machines and workstations in the factory but also the support procedures that make them work. In this entry, particular attention will be paid to those aspects of manufacturing systems that are of particular interest from the point of view of production technology.

#### History

Manufacturing historical roots date back to the eighteenth century: a number of different manufacturing paradigms have been proposed with the aim to meet the several targets defined by the changing market requirements.

Research studies (Mehrabi et al. 2002) identify three major periods that exemplify the key changes in the focus of manufacturing systems:

- Precomputer numerical control
- Computer numerical control (CNC)
- Knowledge epoch

The first manufacturing paradigm introduced in the pre-CNC epoch is mass production: this paradigm enabled the manufacturing of high volumes of one specific part type on dedicated manufacturing systems (DMS), cost-effectively and with the required quality. The core elements of the dedicated manufacturing systems are transfer lines, assembly stations, fixed tooling, and dedicated automation processes. The emphasis was focused on high production rates, since few product variations were required.

In the CNC epoch, from the 1960s to the 1990s, the emphasis on cost-effectiveness of production was enhanced together with a particular focus on product quality improvement. This trend was supported by the introduction of CNC machines, as they were able to provide for more accurate manufacturing process control and then to achieve better quality products.

In this period, production paradigms developed in the Japanese manufacturing industry became largely widespread. Among these are the known kaizen, aimed at the continuous improvement of products and processes; the just-in-time (JIT) approach, supporting the elimination or minimization of inventory as the ideal target to reduce costs; and total quality management (TQM), focused on increased and faster communications with customers in order to be able to better meet their requirements.

An important paradigm conceived during the CNC period is lean manufacturing, whose key principles are perfect first-time quality, waste minimization by removing all activities that do not add value, continuous improvement, and flexibility.

Another relevant paradigm is cellular manufacturing, aimed to improve productivity through the employment of manufacturing cells. The main concept behind cellular manufacturing is the so-called group technology, which consists in clustering parts into families with similar characteristics that can be processed by the same group of machines, tooling, and people with only minor changes on procedure or setup.

Around the 1960s, flexible manufacturing systems (FMS) were introduced to address changes in work orders, production schedules, part programs, and tooling for the production of a family of parts. The objective of a FMS is to realize the cost-effective manufacturing of several types of parts that can change over time, with short changeover time, at the required volume and quality always on the same system, in order to simultaneously achieve productivity and flexibility. The main components of a FMS are CNC manufacturing machines, tools to operate CNC machines, robots, and automated material handling systems (MHS).

The knowledge epoch was then characterized by intensified global competition and progress in computer and information technology. Every effort is made by manufacturers to respond faster to the market by producing higher quality products at lower costs and in smaller quantities. Agile manufacturing was introduced as a new approach to respond to rapid change due to competition.

In this context, reconfigurable manufacturing systems (RMS) were introduced in the mid-1990s as a cost-effective reaction to market demands for responsiveness and customization (Koren et al. 1999). A RMS is designed for rapid change in structure, as well as in hardware and software components, in order to quickly adjust production capacity and functionality within a part family in response to sudden changes in market. A subset of reconfigurability is represented by scalability, which implies changing configuration by adding (or removing) the configuration elements, and is one of the principle enablers of changeable manufacturing (Putnik et al. 2013).

Finally, in recent years, new paradigms based on the integration of ICT key enabling technologies such as cyber-physical systems and cloud computing have been introduced (Monostori 2014; Wang et al. 2014).

## Manufacturing Systems Components

Manufacturing systems include production facilities (machines, manual workstations, automatic plants, material flow systems, etc.) which are linked with each other for a certain type of production, as well as support systems, i.e., the procedures and systems to manage production and solve the technical and logistics problems associated with designing the products, planning the processes, ordering materials, controlling work in process as it moves through the plant, and delivering products to the customer.

As regards manufacturing facilities, in general, two areas can be identified (Chryssolouris 2006):

- The processing area, where materials are processed and individual parts or components are fabricated
- The assembly area, where parts or components are joined together in a subassembly or final product

The main components of a manufacturing facility are (Groover 2000):

- Production machines
- Tools, fixtures, and other related hardware
- Assembly/disassembly
- Material handling system
- Human workers
- Computer systems

### Production Machines

In modern manufacturing systems, most of the actual processing or assembly work is accomplished by machines or with the aid of tools. Machines can be classified as (1) manually operated, (2) semiautomated, or (3) fully automated (Groover 2000). Manually operated machines are directed or supervised by a human worker, who must be always present. A semiautomated machine performs a portion of the work cycle under some form of program control, and a human worker performs loading and unloading it or other tasks each cycle. An example of this category is a CNC machine tool controlled for most of the work cycle by a part program but requiring a worker to unload the finished part and load the next workpiece at the end of the part program. On the other hand, a fully automated machine is capable to operate for extended periods of time, longer than one work cycle, with no human attention. A location in the factory where a task or operation is accomplished by an automated machine, a worker-and-machine combination, or a worker using hand tools and/or portable powered tools is called workstation.

### Tools and Fixtures

Tooling requirements for any manufacturing operation depend on the process requirements, the size and type of product, and the quantity of products to be manufactured. Fixtures, clamps, and jigs are the devices used to hold pieces in actual manufacturing operations or for purposes of measurement and inspection. Fixtures can be dedicated, if designed and made for specific workpiece shapes and dimensions and for specific tasks, or they can be flexible, if capable to accommodate a range of shapes and dimensions.

### Assembly/Disassembly Systems

Most products consist of many parts, and their assembly requires considerable care and planning. There are three basic categories of assembly systems: manual, high-speed automatic, and robotic (Kalpakjian and Schmid 2002). Manual systems are generally convenient for complex parts in small lots. High-speed automated systems use transfer mechanisms designed specifically for assembly. In robotic assembly systems, one or more robots can work at a single workstation or at a multi-station assembly system.

### Material Handling System

During a typical manufacturing operation, raw materials and parts are moved from storage to machines, from machine to machine, and from inspection to assembly, to inventory, and finally to shipment (Kalpakjian and Schmid 2002). Material handling is defined as the functions and systems associated with the transportation, storage, and control of materials and parts in the total manufacturing cycle of a product. For small-batch operations, raw materials and parts can be handled and transported by hand, but this method is time consuming and hence costly. Moreover, it can be unsafe to the operator because of the weight and shape of the parts or other environmental factors.

Hence, several types of equipment can be used to move materials, such as conveyors, rollers, self-powered monorails, carts, forklift trucks, and various devices and manipulators. Automated guided vehicles (AGVs) are used extensively as they have high flexibility and they are capable of random delivery to different workstations. AGVs are guided automatically along defined pathways, and their routing can be controlled so that the system optimizes the movement of materials and parts in case of congestion, machine breakdown, etc.

Moreover, loading, unloading, and transferring of workpieces in manufacturing facilities can be carried out reliably and repeatedly by industrial robots.

### Industrial Robots

Applications of industrial robots in manufacturing systems involve not only material handling but also other tasks such as spot welding, finishing operations like deburring, grinding and polishing, spray painting, automated assembly, and inspection. Different categories of robots are available today: Cartesian, cylindrical, spherical, and anthropomorphic. The selection of the most suitable robot depends on many factors such as the required degrees of freedom, payload, work envelope, and repeatability.

### Human Workers

Human workers are referred to as direct labor if they directly add to the value of the product by performing manual work on it or by controlling the machines that perform the work. In automated manufacturing systems, direct labor is needed to perform activities such as loading and unloading parts to and from the system and changing tools. Moreover, human workers are also needed to manage or support the system as computer programmers, computer operators, part programmers for CNC machine tools, maintenance and repair personnel, and similar indirect labor tasks.

### Computer Systems

In modern manufacturing systems, computers are used extensively in all the stages involved in part manufacturing, including product design, process planning, production system design, and process control (Mehrabi et al. 2002). Potential benefits of using computers in manufacturing include reduced costs and lead times in all engineering design stages, improved quality and accuracy, minimization of errors and their duplication, more efficient analysis tool, and accurate control and monitoring of the machines/processes. Computer-aided design (CAD) involves the use of computers in the design and analysis of products and processes. On the other hand, *computer-aided manufacturing* (CAM) is defined as the effective use of computer technology in manufacturing planning and control. Computers are employed to assist in all phases of product manufacturing, including process and production planning, scheduling, manufacture, quality control, and management. Applications of CAM can be divided into two broad categories: manufacturing planning and manufacturing control. An important feature of CAD/CAM systems is the possibility to program computer numerical control (CNC) machine tools that are directly controlled and monitored by computers in real time. More widely, computer-integrated manufacturing (CIM) implements computer technology in all of the operational and information processing activities related to manufacturing, from order receipt, through design and production, to product shipment. The CIM concept is that all of the operations related to production are incorporated in an integrated computer system to assist, augment, and automate the operations. The computer system is pervasive throughout the organization, touching all activities that support manufacturing, and employs a large common database.

*Concurrent engineering* refers to an approach used in product development in which the functions of design engineering, manufacturing engineering, and other functions are integrated to reduce the elapsed time required to bring a new product to market. Also called *simultaneous engineering*, it might be thought of as the organizational counterpart to CAD/CAM technology.

### Cyber Physical Systems

The recent developments of information technology have driven toward the emergence of new paradigms such as cyber-physical systems (CPS). A CPS is a physical and engineered system whose operations are monitored, coordinated, controlled, and integrated by a computing and communication core (Wang et al. 2014). Cyber-physical systems are "integrations of computation, networking, and physical processes. Embedded computers and networks monitor and control the physical processes, with feedback loops where physical processes affect computations and vice versa." (Monostori 2014).

In the context of manufacturing systems, a cyber-physical production system consists of autonomous, self-configurable production resources (production machines, robots, conveying and storage systems, means of production), which:

- Directly acquire physical data by using sensors and act on the physical world by using actors
- Analyze and store the acquired data and interact both with the physical and the virtual world
- Are networked among each other and within global information systems by wired or wireless communication means
- Use worldwide available data and services
- Dispose of several multimodal human-machine interfaces

CPS relying on the newest and foreseeable further developments of computer science (CS), information and communication technologies (ICT), and manufacturing science and technology (MST) are considered key elements that will lead to the fourth industrial revolution, also known as Industry 4.0. A further step is represented by the integration of sensor networks, embedded systems, radio-frequency identification (RFID), GPS, etc., in a cloud so that manufacturing resources (machines, robots, AGVs, etc.) will be intelligently sensed and connected to the Internet, as well as remotely controlled and managed. This leads to the Internet of Things (IoT), which is the basis to realize cloud manufacturing.

### Performance Measures

A performance measure is a variable whose value quantifies an aspect of the performance of a manufacturing system. Performance measures are either *benefit* measures (the higher the better) or *cost* measures (the lower the better). They can be divided into four categories: time, quality, cost, and flexibility (Chryssolouris 2006). In general, a number of performance measures will be relevant for a given manufacturing system. However, they will differ from one manufacturing system to another.

Performance measures that characterize the behavior of manufacturing systems are:

- Production rate or throughput
- Work in process
- Finished goods inventory
- Probability of blockages and starvations
- Residence time
- Due-time performance
- Reliability
- Fault tolerance
- Productivity
- Product quality
- Cost

### Manufacturing System Design

A manufacturing system design can be defined as the mapping from the performance requirements of a manufacturing system, as expressed by values of chosen performance measures, onto suitable values of decision variables, which describe the physical design or the manner of operation of the manufacturing system (Chryssolouris 2006).

Given performance requirements, the manufacturing system designer must describe a suitable system design. This design can be captured numerically by specifying the values of an appropriate collection of *decision variables.* Examples of decision variables are the number of each type of machine in a manufacturing system. Designing manufacturing systems (mapping performance measures onto decision variables) is a difficult task because of several reasons:

- Manufacturing systems are large and have many interacting components.
- Manufacturing systems are dynamic.

- Manufacturing systems are open systems, which both influence and are influenced by their environment.
- The relationships between performance measures and decision variables cannot usually be expressed analytically. Well-behaved functions do not apply.
- Data **may be** difficult to measure in a harsh processing environment.
- There are usually multiple performance requirements for a manufacturing system, and these may conflict.

The fundamental activity in design is decision making: the design of a manufacturing system is the process of deciding the values of the decision variables of the manufacturing system.

Manufacturing systems design methods and tools fall into three major categories: *operations research*, *artificial intelligence*, and *simulation*.

Operations research makes use of mathematical programming methods, a family of techniques for optimizing (minimizing or maximizing) a given algebraic objective function of a number of decision variables. The decision variables may either be independent of one another or they may be related through constraints.

When mathematical models are difficult to create, artificial intelligence tools, such as search and rule-based systems, can be employed to solve manufacturing design problems.

Finally, computer simulation can be employed to examine the operation of a manufacturing system. The input of a computer simulator is represented by decision variables, which specify the machine parameters (e.g., machine processing and failure rates, machine layout), the workload (e.g., arrivals of raw materials over time, part routings), and the operational rules (e.g., "first in, first out") of a manufacturing system. Starting from a defined initial state, the simulation follows the operation of the model over time, tracking events such as parts movement, machine breakdowns, machine setups, etc. At the conclusion of the simulation, the output provided by the simulator is a set of statistical performance measures (e.g., the average number of parts in the system over time) by which the manufacturing system may be evaluated.

### Manufacturing Systems Life Cycle

The significant reduction in product development time brought about by the use of CAD tools was not paralleled in the design and development of manufacturing systems. These systems must be designed to satisfy certain requirements and constraints that vary over time. Recent improvements in productivity were attributed more to improvements in the design and operation of manufacturing systems, as well as the design of products, than to manufacturing processes or technology improvements. Some modern design theories and methodologies have been applied to the design of manufacturing systems. In the context of manufacturing systems, one can envisage a life cycle, which includes the initial system design and synthesis, modeling, analysis and simulation, realization and implementation, operation, and redesign/reconfiguration phases. Both soft and hard reconfiguration and flexibility can extend the utility, usability, and life of manufacturing systems.

## Monitoring and Control of Manufacturing Systems

Manufacturing systems control involves:

- Process monitoring and control, which is concerned with observing and regulating the production equipment and manufacturing processes in the plant. Applications of computer process control include transfer lines, assembly systems, NC, robotics, material handling, and flexible manufacturing systems. To achieve precision in machining, manufacturing processes can be controlled by using real-time data collected from sensors located at different locations of the workpiece, tool, and machine.
- Quality control, which includes a variety of approaches to ensure the highest possible quality levels of the manufactured product.
- Shop floor control, which refers to production management techniques for collecting data from factory operations and using the data to help control production and inventory of the factory.

- Inventory control, which is concerned with maintaining the most appropriate levels of inventory in the face of two opposing objectives: minimizing the investment and storage costs of holding inventory and maximizing service to customers.

## Cross-References

- ▶ Computer-Aided Design
- ▶ Computer-Aided Manufacturing
- ▶ Computer Numerical Control
- ▶ Factory
- ▶ Flexible Manufacturing System
- ▶ Handling
- ▶ Machine Tool
- ▶ Manufacturing
- ▶ Production
- ▶ Productivity
- ▶ Robot
- ▶ Simulation of Manufacturing Systems
- ▶ System

## References


Chryssolouris G (2006) Manufacturing systems: theory and practice. Springer, New York

CIRP Dictionary of Production Engineering (2004) Manufacturing systems, vol 3. Springer, Berlin

Groover MP (2000) Automation, production systems, and computer-integrated manufacturing, 2nd edn. Prentice Hall, Englewood Cliffs

Kalpakjian S, Schmid SR (2002) Manufacturing processes for engineering materials, 4th edn. Prentice Hall, Englewood Cliffs

Koren Y, Heisel U, Jovane F, Moriwaki T, Pritschow G, Ulsoy G, Van Brussel H (1999) Reconfigurable manufacturing systems: a keynote paper. Ann CIRP 48(2):527–540

Mehrabi MG, Ulsoy AG, Koren Y (2002) Manufacturing systems and their design principles. In: Hurmuzlu Y, Nwokah ODI (eds) The mechanical systems design handbook: modeling, measurement, and control. CRC Press, Boca Raton, pp 1–11

Monostori L (2014) Cyber-physical production systems: roots, expectations and R&D challenges. In: Variety management in manufacturing – proceedings of the 47th CIRP conference on manufacturing systems, Procedia CIRP 17, pp 9–13

Putnik G, Sluga A, ElMaraghy H, Teti R, Koren Y, Tolio T, Hon B (2013) Scalability in manufacturing systems design and operation: state-of-the-art and future developments roadmap. CIRP Ann Manuf Technol 62(2):751–774

Wang L, Gao R, Ragai I (2014) An integrated cyber-physical system for cloud manufacturing. In: Proceedings of the ASME international manufacturing science and engineering conference (MSEC2014), Detroit, Michigan, 9–13 June 2014. Materials; micro and nano technologies; properties, applications and systems; sustainable manufacturing, vol 1. ASME, New York, pp V001T04A029. Paper No. MSEC2014-4171


# Mass Customization


Mitchell M. Tseng[1,2], Yue Wang[3] and Roger J. Jiao[4]

[1]Feng Chia University, Taichung, Taiwan

[2]The Hong Kong University of Science and Technology, Hong Kong, China

[3]Hang Seng Management College, Hong Kong, China

[4]The George M. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA, USA


## Synonyms

Personalization

## Definition

Mass customization aims to deliver products and services that best meet individual customers' needs with near mass production efficiency (Tseng et al. 1996). In this paradigm, it is critical to provide individually designed products and services by considering every customer as an individual through process agility, flexibility, and integration of product lifecycle. A brief summary of the basic properties that make mass customization unique is illustrated in Table 1.

Mass customization implies a shift of design and production paradigm from "made-to-stock" to "made-to-order." It challenges the conventional product development and supply chain management, calling for adopting mass production

**Mass Customization, Table 1** Properties of mass customization (Adapted from Chen et al. 2009)

| | Mass customization (MC) |
|---|---|
| Goal | Delivering affordable goods and services with enough variety and customization that everyone finds nearly exactly what they want |
| Economics | Economies of scope and customer integration |
| Focus | Variety and customization through flexibility and responsiveness |
| Product | Product family and standardized modules assembled based on customer needs |
| Key features | Unpredictable demand pattern<br>Heterogeneous niches<br>Integrated goods and services<br>Short product development cycles<br>Short product life cycles |
| Organization | Flexible and adaptive |
| Customer involvement | In order to meet the customer requirements with efficiency and effectiveness, active customers' involvement throughout the product life cycle is essential. Thus, user innovation, codesign, customer configuration, and others have become important tools in MC. |

approaches to accommodate "high-variety-low-volume" production. In order to support the paradigm shift derived by the customization process, the enterprise should reconsider the entire value chain to leverage upon three pillars: time-to-market, variety, and economy of scale.

Mass customization was first coined by Stan Davis in Future Perfect (Davis 1987) and later developed by Pine II (1993). It embarks a paradigm shift for the enterprise to offer products and services best catering to individual customer's needs whereas keeping near-mass production efficiency (Tseng et al. 1996). The key feature of mass customization is the capability to integrate the product varieties derived from the individual customer's needs with repetition of modularity and the efficiency of mass production, so that the products are affordable due to low product cost achieved by the scale of economy in production.

Traditional mass production leverages upon economies of scale that emphasizes reducing the average per unit cost of the products and services by increasing the scale of production for a single product type. The key of mass production efficiency is to produce and deliver more of the same design of a given product or service by defraying the fixed cost with higher production quantities. In addition to economies of scale, mass customization must achieve economies of scope, which aims to lower the average per unit cost by expanding the number of products and services to be offered. Compared to economies of scale, economies of scope is a similar but different concept, in that it is not about making a lot vs. a little of the same product, but about making different but compatible products and services. By using the same facilities, equipment, labor force, technologies, etc., an enterprise can still produce with product diversification to increase revenue. The theory is that offering several different products and services can be done more efficiently than relying on standard products and services, as the fulfillment process can distribute the costs over a greater revenue base. Producing and delivering a differentiation or varied products and services by taking advantage of many of the existing capabilities of design and production is critical to product diversification.



## Theory and Application

### Design for Mass Customization

Design for mass customization (DFMC) calls for extensive coordination between many disciplinary emphases. In general, it goes beyond the traditional territory of product design and involves more front-end business and marketing efforts. At the backend, the DF'X' mindset is extended to take into account downstream production and logistics concerns. Such a complex engineered system requires systematic management throughout customization and personalization decision-making. The decision framework of DFMC along the entire spectrum of product realization can be positioned according to axiomatic design (Suh 2001). In a holistic view, DFMC encompasses consecutively five domains, namely the customer, functional, physical, process, and logistics domains (Tseng et al. 2010). Customization and personalization decision-making involves a series of "what-how" mappings between these domains.

### Understanding Customer Needs

The customer domain is characterized by a set of customer needs (CNs) that are generally categorized as legacy and latent CNs. The CNs are translated into functional requirements (FRs) in the functional domain, in which the specification of a product ecosystem is formulated by taking into account customer and engineering concerns. One crucial step of design for mass customization is to understand individual customer's needs and transform them into functional requirements. The mapping between the customer and functional domains constitutes the front-end issues associated with customization and personalization. As a "codesigner," the customer can directly interact with the producer to express the requirements or even directly design the product, usually through a web-based interface.

However, the task of understanding and characterizing customer needs is challenging (Wang and Tseng 2011). Customer needs are subjective. Each individual customer's perceptions of the product depend largely on complicated internal and external factors and differ from person to person. For example, when selecting a cell phone, different customers may have totally different perceptions of aesthetics, comfort, and easy-to-use toward the same product. The levels of subjective preferences and the corresponding scales may vary significantly across customers. In addition, customer needs and requirements are context dependent. Customers may vary in their preferences and decision-making criteria due to the purchase situation changes. The external factors like mood, emotion, or impulsive feeling can also affect their preferences and requirements. Since it has been acknowledged that the key to product success relies on a better understanding of the voice of the customer and on better links between the preference of the customers, including artistic appreciation, sensory feedbacks, and value judgment with the capability of the companies, it is imperative to discover new ways to characterize and incorporate customer needs in mass customization practice.

## Modularity and Product Family Architecture

In order to take advantage of economies of scale while trying to serve customers as individuals, product modularity and the underpinning effective product family architecture have been considered as effective approaches to achieve mass customization. Product family design offers a systematic instrument to define product platform, the product architecture, and product families. Product platform is "a set of subsystems and interfaces developed to form a common structure from which a stream of derivative products can be efficiently developed and produced" (Meyer and Lehnerd 1997). Product architecture planning is mainly concerned with how a product is arranged into physical units and how these units interact (Ulrich and Eppinger 1995). With various adoptions of different product models, Erens and Verhulst (1997) described the architecture of product families. Fujita and Ishii (1997) discussed design for variety in terms of structuring essential tasks and issues associated with variety design. They also tried to optimize the systems structure and the configuration of product families simultaneously (Fujita et al. 1998). However, their work focuses on computational support instead of product architecture planning. Tseng and Jiao (2001) recognized the rationale of a product family architecture with respect to design for mass customization. They addressed an efficient method to tailor different products according to different customers' requirements based on a common product family platform. They also observed the difference between customer-perceived variety in terms of functionality and technical variety, which results in different variety design themes.

There are two types of prevailing product family design, scalable product family design, and configurational product family design (Jiao et al. 2007; Jiao 2011). Simpson first proposed the scalable approach by using scaling variables at different dimensions to satisfy a variety of customer needs (Simpson 2004). There are two major tasks in scalable product family design. The first one is to determine the appropriate platform. It is followed by the step of optimizing common and distinctive variables' values to better satisfy performance and economics requirements. In a nutshell, the scalable product configuration allows to employ scaling variables that can shrink or stretch the platform in various dimensions to satisfy diverse customer needs while other variables are kept constant. Thus, the important issues are to first decide which variables should take common value in the product family and then determine the optimal value of the common and distinctive variables in terms of customer needs and design requirements. In modular product configuration, the product is designed by adding, substituting, and/or removing functional modules.

The other stream of product family design is configurational product family design based on modular product architectures. It is also called module-based product family design (Ulrich 1995). The modular product configuration takes advantage of modular components. The product module involves a one-to-one mapping from a functional requirement to the physical product feature. The product infrastructure with the specified decoupled interfaces between components allows each module to be changed independently. Various modules can be introduced independently to satisfy customer's heterogeneous needs.

## Configuration

The prevailing practice of DFMC manifests itself through a configure-to-order paradigm, which means satisfying explicit customer needs and building upon the legacy design. Product configuration systems serve as an important enabling toolkit to realize mass customization. Basically, a product configuration system attempts to elicit customer needs and map the needs to design parameters (Piller and Tseng 2010; Wang and Tseng 2014c). A product configurator consists of a set of predefined components or attributes, along with their constraints, to regulate the combination of components. It takes customer needs as input and the output is the desired product variant. Traditional study on product configurations focuses on the reasoning in configurations, modeling of configuration knowledge, the reuse of configuration, etc. One trend in current product configuration research is to incorporate more business intelligence factors into configurators, such as product recommendation (Freuder et al. 2003; Junker and Mailharro 2003; Tiihonen and Felfernig 2010; Wang and Tseng 2013), customer emerging needs detection (Urban and Hauser 2004; Wang and Tseng 2014a, b), and improving efficiency of the choice navigation process of customization (Wang and Tseng 2007, 2011; Jalali and Leake 2012). User innovation, data mining, and Web learning lend themselves to be the main techniques of customer requirement acquisition and reasoning about user experience (Zhou et al. 2011a). New cyber-physical platforms, such as Web 2.0, cloud computing, P2P and SecondLife, offer great potential for implementing value chain platforms into online personalization engines that can provide recommendations on latent CNs (Zhou et al. 2011b).

## Fulfillment for Mass Customization



### Flexible Manufacturing for Mass Customization

As the exponentially increased number of process varieties significantly challenges production planning and control of conventional manufacturing process (Tian et al. 2008; Terkaj et al. 2009a), it is critical to have flexible manufacturing processes in mass customization. From a mass customization perspective, two approaches have been employed to improve the flexibility of a manufacturing process. Manufacturing process family is one important approach. The concept is to comprise a set of similar production processes for various products to achieve economies of scale by utilizing the common components and the standardized product platform designed within a product family. Thus, the manufacturer is able to configure the production process with quick response to product design changes, by exploiting the similarity among the product variety and production process (Colledani et al. 2008).

Manufacturing for mass customization also relies on the availability of a flexible manufacturing system. In addition, the system should be incorporated with the advent of modern

Information and Computer Technology (ICT) as well as flexible or reconfigurable manufacturing tools, to reduce the response time from designing a new product to the production ramp-up (Terkaj et al. 2009b). For instance, such a system can produce a new last for shoe production within 5 days since the customized shoe order is received. The system enables designers to change the CAD model easily with the limited additional cost. It is equally important that the flexibility in workforce and production management systems are also key to achieve the seemingly conflicting goals of mass customization. With more educated human resource, decision to meet diverse requirements without increasing cost. Likewise, robust production control is essential to achieve on time delivery with complexity of materials management and logistics to realize mass customization.

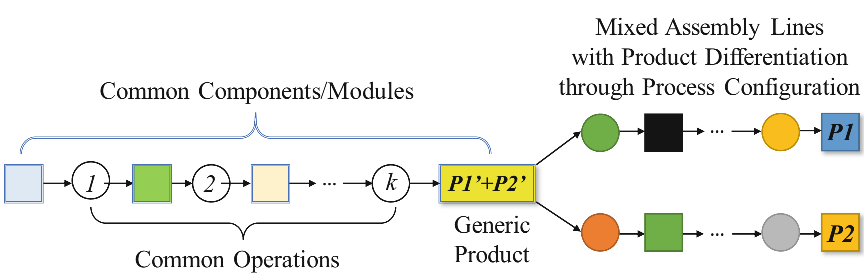
### Reconfigurable Manufacturing System

Product variety can be very high under mass customization regime to cope with the changing product mix and demands. Manufacturing systems for mass customization need to well address the challenges. Reconfigurable manufacturing systems (RMS) were proposed by Koren et al. (1998). An RMS is a system that is designed at the outset for rapid changes in its structure and control in order to adjust its production capacity and functionality within a part family in response to sudden market changes (Koren et al. 1999). Configurations of the manufacturing system play an important role in impacting the performance of the systems. It should be noted that RMS is different with flexible manufacturing systems in the sense that RMS attempts to increase the manufacturer's responsiveness to markets and customers and flexible manufacturing systems aims to increase the variety of parts produced. The flexibility of a RMS is confined within the product family.

### Delaying Differentiation

To manage the high uncertainty and variety in manufacturing systems, delayed product differentiation or postponement strategies are widely used in the industry. They advise to make a generic or family product at the beginning of the manufacturing process and differentiate into a specific end-product in the later stage when more information about the demand is obtained. Thus, the point where the different products take on their unique characteristics is postponed. The processes and assemblies are common up to the point of differentiation. This kind of postponement reduces cost and improves the responsiveness of the assembly systems (Lee and Tang 1997; Ko and Hu 2008).

Figure 1 illustrates how delayed product differentiation is achieved through process configuration by postponing variety fulfillment. Multiple end-products can share those common components/modules and the corresponding fulfillment processes at initial stages, leading to a generic product that is indifferent in end-product variety. At a certain point, custom components/modules or specialized processes are enacted to customize the generic product to different end-products. Therefore, mass customization is empowered by building product platforms and reengineering the manufacturing processes to postpone decisions on specific products as far as possible.




**Mass Customization, Fig. 1** Postponement of variety throughout the fulfillment process

### On-Demand Manufacturing System

To increase the responsiveness to customer demands, it is critical for manufacturing systems to fabricate personalized product features and modules and assemble these modules with other manufacturer supplied modules flexibly. Additive manufacturing has been considered as an enabling technology toward personalization (Srinivasan and Bassan 2012). It can create 3D solid objects directly from a CAD model cost-effectively. In addition, a cost-effective on-demand assembly system should be able to configure and reconfigure products in response to customers' personalized designs.

### Cyber-Physical Systems

Cyber-physical systems refer to engineered systems that are built from and depend upon the synergy of computational and physical components (NSF report – Cyber-physical systems 2012). To support the distributed personalization design collaboration and on-demand manufacturing, it is necessary to integrate computational tools with the physical design and manufacturing systems. The development of new user interface methods and tools for personalized production will be critical to support the scalable user experience and collaborative, distributed design approaches. Considering users may share and view the design with likeminded people, we can leverage on existing cyber-social networking infrastructures to support these users. Methodology to identify emerging customer needs will be needed to address the potential business opportunity of new market and new product development.

## Future Direction

One of the main streams of MC is to better define customer requirements. Customer participation in the design process has shown to be the most promising way of getting the requirements efficiently and effectively (Tseng 2003). Currently, the whole process is mainly managed by the designer and the product is assembled and delivered by the producer. However, with the new interactive computing technology, it is possible for consumers to control and dominate the process in a virtual environment. Thus, the role of the designer will be shifted to product platforms with sufficient supports to assist the process. It means that the product can be customized at any time when the consumer thinks it is necessary to do so, even after the product has been purchased. Such freedom would offer significant opportunities for consumers to dynamically adapt the product to their needs and reflect their identity and efficacy through the creative design and modifications throughout the lifespan of the product. Thereby, customers become more connected. Products and services are increasingly knitted to a larger ecosystem of interacting objects. A product ecosystem can be considered as a dynamic unit that consists of all products and users, functioning together with its surrounding ambiance, as well as their interactive relations and business processes. Looking at the whole sum of interacting objects and understanding the flow patterns of the ecosystem are for the future of mass customization.

Looking forward, with the entry barrier reduced in both customer requirements acquisition at the front end and product delivery at the back end, we can thus extrapolate mass customization to open customization, along with the similar concepts of open system and open innovation. Open customization, still a working definition, is a paradigm that motivates people to participate, to create, to learn, to acquire, and to recover in providing goods and services to fulfill individual needs, not only products but also the process of producing, with fair competition.

Finally, the social aspect of product and service platforms in mass customization is emerging as an interesting research area, as a product-service ecosystem is often associated with social networks. Interactive information sharing among customers is becoming fast and convenient over the Internet with online social networks (e.g., Facebook) or review sections of shopping websites (e.g., Amazon). The increasing availability of data about peer interactions and the popularity of marketing communication techniques based on such interactions have led to an even greater interest in understanding the effects of peer influence on customers' choice decisions of product offerings (Iyengar et al. 2010). The extensive reach of the

Web and the prevalence of social networking sites have made large amounts of data on social networks easily available, which has recently resulted in their recognition as an important tool for marketing (van den Bulte and Wuyts 2007). Because the market is shifting to the online environment and due to the competitive nature of industries, it is important for firms to benefit from such information with appropriate marketing and product family design strategies (Panchal and Messer 2011). While the effect of peer influence has been well documented in marketing research (Childers and Rao 1992), social network effects have generally been neglected within the product family design process (Günnec 2012). Recent advances in social media that allow better access to social networks of customers have profound technical and economic implications for product and service platform development. A phenomenal trend is emerging toward social commerce (Decker 2007), which makes academia and industries recall the dot-com and e-commerce revolution of the previous decade ago. Abundant research opportunities exist in response to the emerging trend of open architecture product and service platform development that aims to leverage upon systems, humans, cybernetics, and businesses.

## Cross-References

- ▶ Cyber-Physical Systems
- ▶ Flexible Manufacturing System
- ▶ Modular Design
- ▶ Product Architecture
- ▶ Reconfigurable Manufacturing System

## References


Chen SL, Wang Y, Tseng MM (2009) Mass customization as a collaborative engineering effort. Int J Collab Eng 1(1/2):152–167

Childers TL, Rao AR (1992) The influence of familial and peer based reference groups on consumer decisions. J Consum Res 19:198–211. https://doi.org/10.1086/209296

Colledani M, Terkaj W et al (2008) Development of a conceptual reference framework to manage manufacturing knowledge related to products, processes and production systems. In: Bernard A, Tichkiewitch S (eds) Methods and tools for effective knowledge life-cycle-management. Springer, Berlin/Heidelberg, pp 259–284. https://doi.org/10.1007/978-3-540-78431-9_15

Davis SM (1987) Future perfect. Addison-Wesley Publishing, Reading

Decker S (2007) The big idea behind social commerce. http://www.imediaconnection.com/content/15372.asp. Accessed 30 Dec 2016

Erens F, Verhulst K (1997) Architectures for product families. Comput Ind 33(2–3):165–178. https://doi.org/10.1016/S0166-3615(97)00022-5

Freuder EC, Likitvivatanavong, C, Moretti M, Rossi F, Wallace RJ (2003) Computing explanations and implications in preference-based configurators. In: recent advances in constraints: joint ERCIM/CologNet international workshop on constraint solving and constraint logic programming, Cork, 19–21 June 2002. Selected papers, vol 2627 of the series lecture notes in computer science, pp 76–92. https://doi.org/10.1007/3-540-36607-5_6

Fujita K, Ishii K (1997) Task structuring toward computational approaches to product variety design. In: Proceedings of DETC'97. 1997ASME design engineering technical conferences, 14–17 Sept 1997, Sacramento. Paper No. DETC97/DAC-3766. ASME, New York

Fujita K, Akagi S, Yoneda T, Ishikawa M 1998 Simultaneous optimization of product family sharing system structure and configuration. In: Proceedings of the ASME, design engineering technical conferences, design for manufacturing (DFM'98), Atlanta. ASME, New York. Paper No. DETC98/DFM-5722

Günnec D (2012) Integrating social network effects in product design and diffusion. PhD dissertation, University of Maryland, Maryland

Iyengar R, van den Bulte C, Valente TW (2010) Opinion leadership and social contagion in new product diffusion. Market Sci 30(2):195–212. https://doi.org/10.1287/mksc.1100.0566

Jalali V, Leake D (2012) Customizing question selection in conversational case-based reasoning. In: Proceedings of the twenty-fifth international florida artificial intelligence research society conference, Marco Island, Florida, pp 329–334

Jiao RJ 2011 Prospect of design for mass customization and personalization. In: ASME international design engineering technical conferences & computers and information in engineering conference, Washington, DC. Palo Alto, Association for the Advancement of Artifical Intelligence

Jiao J, Simpson TW, Siddique Z (2007) Product family design and platform-based product development: a state-of-the-art review. J Intell Manuf 18(1):5–29. https://doi.org/10.1007/s10845-007-0003-2

Junker U, Mailharro D (2003) Preference programming: advanced problem solving for configuration. Artif Intell Eng Des Anal Manuf (AI EDAM) 17(1):13–29. https://doi.org/10.1017/S089006040317103X
Ko J, Hu SJ (2008) Balancing of manufacturing systems with complex configurations for delayed product differentiation. Int J Prod Res 46(15):4285–4308. https://doi.org/10.1080/00207540601078047
Koren Y, Hu SJ, Weber TW (1998) Impact of manufacturing system configuration on performance. CIRP Ann Manuf Technol 47(1):369–372. https://doi.org/10.1016/S0007-8506(07)62853-4
Koren Y, Heisel U, Jovane F, Moriwaki T, Pritschow G, Ulsoy G, Van Brussel H (1999) Reconfigurable manufacturing systems. CIRP Ann Manuf Technol 48(2):527–540. https://doi.org/10.1016/S0007-8506(07)63232-6
Lee HL, Tang CS (1997) Modelling the costs and benefits of delayed product differentiation. Manag Sci 43(1):40–53
Meyer MH, Lehnerd AP (1997) The power of product platform – building value and cost leadership. Free Press, New York
National Science Foundation Cyber-Physical System Program Solicitation (NSF 13-502) (2012) http://www.nsf.gov/pubs/2012/nsf12520/nsf12520.htm. Accessed 23 Nov 2016
Panchal JH, Messer M (2011) Extracting the structure of design information from collaborative tagging. J Comput Inf Sci Eng 11(4): 041007(041001–041011). https://doi.org/10.1115/1.3617447
Piller FT, Tseng MM (eds) (2010) Handbook of research in mass customization and personalization. World Scientific, New Jersey
Pine BJ II (1993) Mass customization: the new frontier in business competition. Harvard Business School Press, Boston
Simpson TW (2004) Product platform design and customization: status and promise. Artif Intell Eng Des Anal Manuf 18(1):3–20. https://doi.org/10.1017/S0890060404040028
Srinivasan V, Bassan J (2012) Manufacturing the future: 10 trends to come in 3D printing. Forbes/Tech 7 Dec 2012. http://www.forbes.com/sites/ciocentral/2012/12/07/manufacturing-the-future-10-trends-to-come-in-3d-printing/#50758cbb2ba3/. Accessed 21 Nov 2016
Suh N (2001) Axiomatic design: advances and applications. Oxford University Press, New York
Terkaj W, Tolio T, Valente A (2009a) Focused flexibility in production systems. In: ElMaraghy HA (ed) Changeable and reconfigurable manufacturing systems. Springer, London, pp 47–66. https://doi.org/10.1007/978-1-84882-067-8_3
Terkaj W, Tolio T et al (2009b) A review on manufacturing flexibility. Design of flexible production systems: methodologies and tools. Springer-Verlag Berlin Heidelberg. https://doi.org/10.1007/978-3- 540-85414- 2_3
Tian X, Huang L et al (2008) Exploring parameterised process planning for mass customisation. In: Advanced design and manufacture to gain a competitive edge. Springer, London, pp 643–652. https://doi.org/10.1007/978-1-84800-241- 8_65
Tiihonen J, Felfernig A (2010) Towards recommending configurable offerings. Int J Mass Customisation 3(4): 389–406. https://doi.org/10.1504/IJMASSC.2010.037652
Tseng MM, Jiao J (2001) Mass customization. In: Salvendy G (ed) Handbook of industrial engineering: technology and operations management, 3rd edn. Wiley, Hoboken, pp 684–709. https://doi.org/10.1002/9780470172339.ch25
Tseng MM, Jiao RJ, Merchant ME (1996) Design for mass customization. Ann CIRP 45(1):153–156. https://doi.org/10.1016/S0007-8506(07)63036-4
Tseng MM, Kjellberg T, Lu SC-Y (2003) Design in the new e-commerce era. CIRP Ann Manuf Technol 52(2): 509–519. https://doi.org/10.1016/S0007-8506(07)60201-7
Tseng MM, Jiao RJ, Wang C (2010) Design for mass personalization. Ann CIRP 59(1):175–178. https://doi.org/10.1016/j.cirp.2010.03.097
Ulrich K (1995) The role of product architecture in the manufacturing firm. Res Policy 24(3):419–440. https://doi.org/10.1016/0048-7333(94)00775-3
Ulrich K, Eppinger SD (1995) Product design and development. McGraw-Hill, New York
Urban GL, Hauser JR (2004) 'Listening-in' to find and explore new combinations of customer needs. J Mark 68(2):72–87. https://doi.org/10.1509/jmkg.68.2.72.27793
van den Bulte C, Wuyts S (2007) Social networks and marketing. Marketing Science Institute, Cambridge, MA
Wang Y, Tseng MM (2007) An approach to improve the efficiency of configurators. In: IEEE international conference on industrial engineering and engineering management, Singapore, 2–5 Dec 2007. https://doi.org/10.1109/IEEM.2007.4419409
Wang Y, Tseng MM (2011) Adaptive attribute selection for configurator design via shapley value. Artif Intell Eng Des Anal Manuf 25(2):185–195. https://doi.org/10.1017/S0890060410000624
Wang Y, Tseng MM (2013) Customized products recommendation based on probabilistic relevance model. J Intell Manuf 24(5):951–960. https://doi.org/10.1007/s10845-012-0644- 7
Wang Y, Tseng MM (2014a) Identifying emerging customer requirements in early design stage by applying Bayes factor based sequential analysis. IEEE Trans Eng Manag 61(1):129–137. https://doi.org/10.1109/TEM.2013.2248729
Wang Y, Tseng MM (2014b) Attribute selection for product configurator design based on Gini index. Int J Prod Res 52(20):6136–6145
Wang Y, Tseng MM (2014c) Incorporating tolerances of customers' requirements for customized products. Ann CIRP 63(1):129–131
Zhou F, Xu Q, Jiao RJ (2011a) Fundamentals of product ecosystem design for user experience.

Res Eng Des 22(1):43–61. https://doi.org/10.1109/TSMCA.2011.2147309
Zhou F, Jiao RJ, Xu Q, Takahashi K (2011b) User experience modeling and simulation for product ecosystem design based on fuzzy reasoning petri nets. IEEE Trans Syst Man Cybern Syst Hum 42(1):201–212. https://doi.org/10.1109/TSMCA.2011.2147309

# Material Flow

Gino Dini[1] and Dieter Spath[2]
[1]Department of Civil and Industrial Engineering, University of Pisa, Pisa, Italy
[2]Institute of Human Factors and Technology Management Institute Fraunhofer IAO (Fraunhofer Gesellschaft), University of Stuttgart, Stuttgart, Germany

## Synonyms

Internal logistics; Material handling

## Definition

The term "material flow" represents, in general, the movement of material through a production system. More specifically, in assembly line, it is a set of operations by which a product is taken from a loading station, passes through several assembly steps, and arrives to the final dispatch. This set of operations is usually made by using appropriate facilities (transportation systems) such as carriers, conveyors, or vehicles.

Material flow can be included into a more general term of "material handling" or "internal logistics" which means not only the movement of parts but also their storage, control, coding, etc.

## Theory and Application

### Transportation Systems in Assembly

Transportation systems used to perform a material flow in assembly operations can be classified into three main categories (Groover 2008):

- Hand trucks
- Conveyors
- Vehicles

In particular, from this point of view, the taxonomy in Fig. 1 can be structured.

Table 1 summarizes the main advantages and disadvantages for each category of transportation system.

#### Hand Trucks

Hand trucks represent the simpler way for moving material in a factory environment. They are driven manually by human workers and they are usually characterized by a low payload and a low rate of deliveries per hour.

The most diffused hand truck configurations are two-wheel hand trucks, four-wheel dollies, and hand-operated forklift trucks.

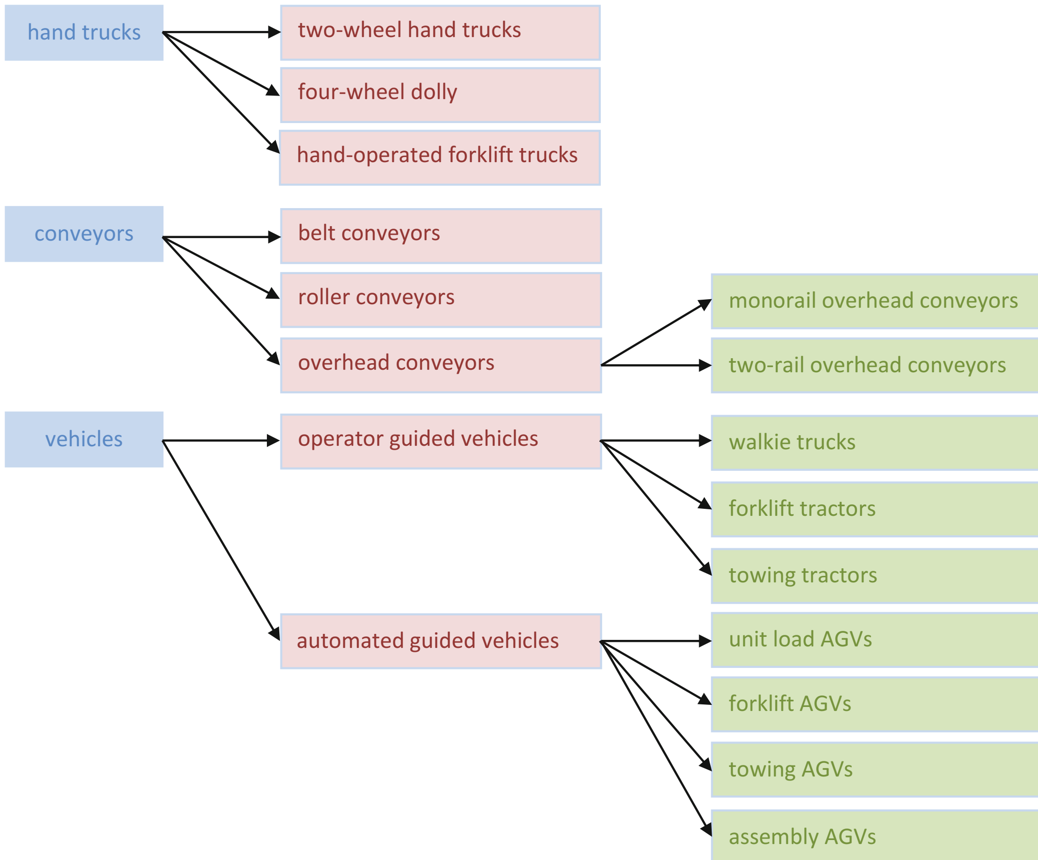
Two-wheel hand trucks are very common and diffused also in nonindustrial applications. They can be easily moved by an operator, but the weight of the product to deliver is limited. The loading of a product is obtained by inserting the ledge underneath it and allowing the object to tilt back and rest on the ledge. Some of them are equipped with a stair-climber device in order to go up and down along stairs.

Dollies are simple platforms with four wheels having different configurations with fixed or swivel caster-type wheels. Usually, they have a payload greater than a two-wheel hand truck, but their mobility is lower.

Hand-operated forklift trucks have two forks that can be inserted by the worker into proper openings of a pallet. Through a lifting mechanism, the pallet can be elevated from the ground (about 10–15 cm) in order to move it. Once the pallet has been positioned, the forks can be lowered and the pallet is placed down onto the ground.

#### Conveyors

Conveyors are mechanical devices used to move single products in an assembly line along a predefined pathway which can be on the floor, overhead, or either. The movement of parts is obtained by placing them directly on the translating or rotating elements of the conveyor. Translating elements




**Material Flow, Fig. 1** Taxonomy of transportation systems



**Material Flow, Table 1** Main features of transportation systems

| Transportation system | Advantages | Disadvantages | Typical applications |
|---|---|---|---|
| Hand trucks | Low cost | Low payload | Movement of light loads, usually out of high volume processes |
| | High flexibility | Low rate of material flow | |
| | | Dedicated worker | |
| Conveyors | High rate of material flow | Low level of flexibility in routing | Movement of products in medium or high production rates |
| | Great variety of solutions (on the floor or overhead) | Obstructive pathways (on the floor) | |
| Operator-guided vehicles | High payload | Dedicated worker with driving license | Movement of heavy loads in a factory or in a warehouse |
| | High flexibility | | |
| | High rate of material flow | | |
| Automated guided vehicles | High payload | High cost | Movement of products in high flexible manufacturing systems |
| | High flexibility in routing | | |
| | High rate of material flow | | |

can be belts (belt conveyors) or chains (overhead conveyors); rotating elements can be roller or skate-wheels (roller conveyors). Usually the parts to be moved are placed on the conveyor without a precise location. Conveyors can be powered or unpowered: in powered conveyors the movement of belts, chains, or rollers is obtained by using electric motors; in unpowered conveyors, the movement of parts is obtained by exploiting the gravity force (the pathway has a downward slope sufficient to overcome friction).

**Belt Conveyors** Belt conveyors are widely diffused in many applications, not only in assembly but also in other different areas such as in agricultural industry, for bulk material transportation, or in baggage claim areas (Dini 2012).

A belt conveyor is mainly formed by an endless belt translating around two or more rollers. The material is moved by placing it directly on the translating belt. This transportation system can mainly assume two different configurations (Fig. 2):

- Open-loop configuration
- Closed-loop configuration

The open-loop configuration (Fig. 2a) is used for connecting a loading and an unloading station without the need of having a return way. This is the case of moving products without using containers or pallets which should be repositioned to the loading station.

Considering that the belt conveyor is moving at a constant speed $V_{bc}$ [m/min], the time needed for going from the loading to the unloading station is

$$t = L_{bc}/V_{bc}[\text{min}] \tag{1}$$

being $L_{bc}$ [m] the length of the belt conveyor.

An important process parameter is represented by the material flow $F_m$. It represents the number of parts that the conveyor is able to deliver in the time unit [parts/min]. This value obviously depends on the speed $V_{bc}$ but also on the distance $d_{bc}$ between each part along the belt. In particular, it results:

$$F_m = V_{bc}/d_{bc} \tag{2}$$

Generally speaking, the material flow $F_m$ has to be less or equal to the loading and unloading rates obtained using a human operator or a robot at the beginning and at the end of the line. Being $t_l$ and $t_u$ [min], respectively, the loading and the unloading time, the following relation has to be verified:

$$F_m \leq \min \{ 1/t_l; 1/t_u \} \tag{3}$$

The closed-loop configuration (Fig. 2b) is used when the parts to deliver are placed inside a container or a pallet which has to be returned (empty) to the loading station. This configuration can also be used when the parts have to be recirculated before unloading, in order to create a sort of a storing buffer (in the same way which occurs in the baggage claim area of the airports).

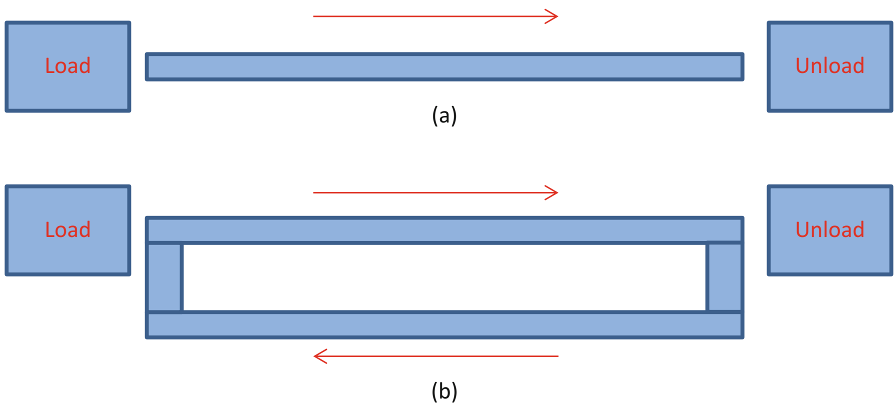
Obviously, the same relations seen for the rectilinear configuration are also valid in this case. In addition, the number of containers needed along the line has to be evaluated by using the following expression:

$$n_c = L_{tot}/d_{bc} \tag{4}$$

where $L_{tot}$ is the total length of the closed loop. Obviously, $n_c$ must be an integer; therefore, the values of $L_{tot}$ e $d_{bc}$ have to be set in order to satisfy this requirement.

**Roller Conveyors** Roller conveyors consist of a series of rollers positioned with their axes perpendicular to the direction of movement. The movement is obtained by the friction generated by the rotation of the rollers powered by electric motors. The parts to be moved must present a flat bottom surface with a size able to cover a distance equal at least of three or four adjacent rollers. In some cases, and for short paths, the movement can be obtained by gravity, using slightly inclined paths (3–5%) and unpowered rollers, free of rotating.

**Overhead Conveyors** Overhead conveyors are supported from the ceiling or the floor by suspensions and they are very common in assembly




**Material Flow, Fig. 2** Conveyor configurations: (**a**) open loop configuration; (**b**) close loop configuration

lines. They represent the best solution if one of the primary goals to reach by the transportation system is to have unobstructed area on the floor. Furthermore, they can also used in inaccessible zones such as ovens, painting boxes, washing equipments, and tunnels.

Overhead conveyors can be classified in two main types:

- Monorail
- Two rails

Monorail type essentially consists of a chain running inside a track (straight or bent) made of cold rolled sections with pressed steel straddle plates welded on them. The track segments are connected together with bolts. Every conveyor has a drive unit of the chain (caterpillar type) and a tension unit to adjust the tightening of the chain by screws and without counterweights. The product is moved along the track by placing it on a trolley connected to the translating chain and equipped with wheels rolling on the track.

The second type has two rails, one is the power rail and the other is the free rail. The former is the rail exerting the pushing/pulling force for moving the load; the latter supports the weight of the trolley, but it has no driving force. This system is therefore able to disconnect the trolley from the power rail, so that an operator can manually push it and moved it freely.

### Vehicles

A vehicle is a device used to transport objects and equipped with a powered locomotion system and a steering system. A vehicle can be guided by an operator (driver) or by an electronic controller. In this last case, the vehicle is usually named automated guided vehicle (AGV).

A delivery cycle of a vehicle can be schematically described through the following steps (Groover 2008):

- Loading of parts at loading station ($T_L$: loading time [min/del])
- Moving of the loaded vehicle toward the unloading station ($V_L$: loaded vehicle speed [m/min]; $L_L$: length of the path connecting loading and unloading stations [m/del])
- Unloading of parts at unloading station ($T_U$: unloading time [min/del])
- Moving of the empty vehicle toward the loading station to start the next delivery ($V_E$: empty vehicle speed [m/min]; $L_E$: length of the path connecting unloading and loading stations [m/del])

The total delivery cycle time of a vehicle can be calculated by:

$$T_D = T_L + L_L/V_L + T_U + L_E/V_E [min/del] \quad (5)$$

Therefore, the material flow which can be obtained by using this vehicle is:

$$F_m{}' = 60/T_D \quad [del/hour] \tag{6}$$

The material flow evaluated by the previous expression is valid if no time loss occurs during the delivery cycle. A more realistic value can be obtained considering the following corrective factors:

- *Availability factor* $f_A$, which takes into account that a vehicle could stop for failures or other technical problems. This factor represents the rate between the time in which the vehicle is operational and the total production time.
- *Traffic factor* $f_T$ which considers the time losses due to traffic congestion, waiting at the intersections, and waiting at the queue at a loading or unloading station. This value mainly depends on the number of circulating vehicles: $f_T$ usually ranges between 1, in the case of only one vehicle, and 0.85 for more vehicles on the routes.
- *Worker factor* $f_W$ depending on the worker efficiency. In fact, for human-operated vehicles, the performance of the transport system also depends on the efficiency of the operator who drives the truck. It can be defined as the actual work rate done by the worker relative to the expected work rate. In automated guided vehicles, $f_W$ can be assumed equal to one.

Considering the previous factors, a more realistic value of the material flow is given by

$$F_m{}' = 60\, f_A\, f_T\, f_W/T_D \quad [del/hour] \tag{7}$$

The previous value represents the material flow reachable by using only one vehicle. However, if the total delivery requirements in the manufacturing system $F_m$ is greater, more vehicles are necessary on a specific pathway. The number of vehicles required is:

$$n_V = F_m/F_m{}' \tag{8}$$

**Operator-Guided Vehicles** Operator-guided vehicles used in industry are mainly walkie trucks, forklift tractors, and towing tractors.

Walkie trucks can be considered the battery-powered version of the hand-operated forklift trucks. They are equipped with wheeled forks used to lift loads. The worker usually does not ride on the vehicle, but he controls the speed and the steering systems by using a control handle in front of the vehicle. For safety reasons, the maximum speed is limited to about 5 km/h, therefore no more than the normal speed of a human worker.

Forklift tractors use forks to lift and move materials. With respect to walkie trucks, they present the following advantages: higher speed, higher payloads, and capability to lift the loads at different heights in high-density storage racks. This vehicle has a seat for the driver who controls the speed and the movement direction by a conventional pedals and steering wheel. The payload can range from about 450 kg up to more than 4500 kg, and the power system can consist of an electric motor or an internal combustion engine (diesel or liquefied petroleum gas).

Towing tractors are used to pull one or more trailing carts. In industrial areas, they usually transport large amount of materials from a collecting point to a delivery station. They are also diffused for moving luggage in railway stations or airports.

**Automated Guided Vehicles** An AGV is a vehicle automatically controlled for moving along predefined pathways at a given speed. One of the most important features of this transportation system is that the pathways are place on the floor but they are not obstructive.

The guidance systems used to drive the vehicle along the pathways can be mainly classified in two types:

– Wire-guided systems
– Wireless systems

In the wire-guided systems, the pathway is identified by a wire buried into the floor. Three different types exist: induction system, optical system, and magnetic system. The induction system is based on a wire connected to an AC generator which creates a variable magnetic field along the pathway. This field induces a voltage in two coils mounted on the vehicle on the either side with respect to the wire. If the vehicle is centered on the pathway, the induced voltages are equal in the coils, but if the vehicle strays to one side, the voltage in the coils positioned in the opposite side becomes greater than the other. This difference is used to control the steering system and, therefore, for maintaining the vehicle on the track.

The optical system is based on a painted strip used to define the path. An optical sensor is placed on the vehicle able to detect the reflected light by the strip. The signal generated by the sensor is used to control the steering system.

The magnetic system is based on magnets distributed along the track. An on-board sensor detects the magnetic fields generated by each magnet in order to follow the track.

As far as the wireless systems are concerned, the dead reckoning method is frequently adopted in many vehicles; it allows the control of the vehicle in function of the wheel revolutions and the angle of the steering wheel, but it has a low accuracy in long routes which can be increased with the following two methods: correction algorithms to be applied in convenient points along the route and measuring systems of the absolute position of the vehicle obtained through triangulation methods evaluating the distance and/or the direction of some reference points distributed in the working area. One of these methods, based on a rotating laser emitter placed aboard the vehicle, shows a sufficient reliability and accuracy and has been successfully applied in the industry; in this last case, the reference points can be represented by markers supporting a bar code or by simple reflectors.

Different AGV configurations can be used in industry according to the particular task to be performed in a transportation system. The most diffuse type is the unit load AGV normally equipped automatic loading/unloading devices and used to move single products from a working station to another. In assembly lines, a typical configuration is essentially a moving platform which contains the product and the parts to be assembled.

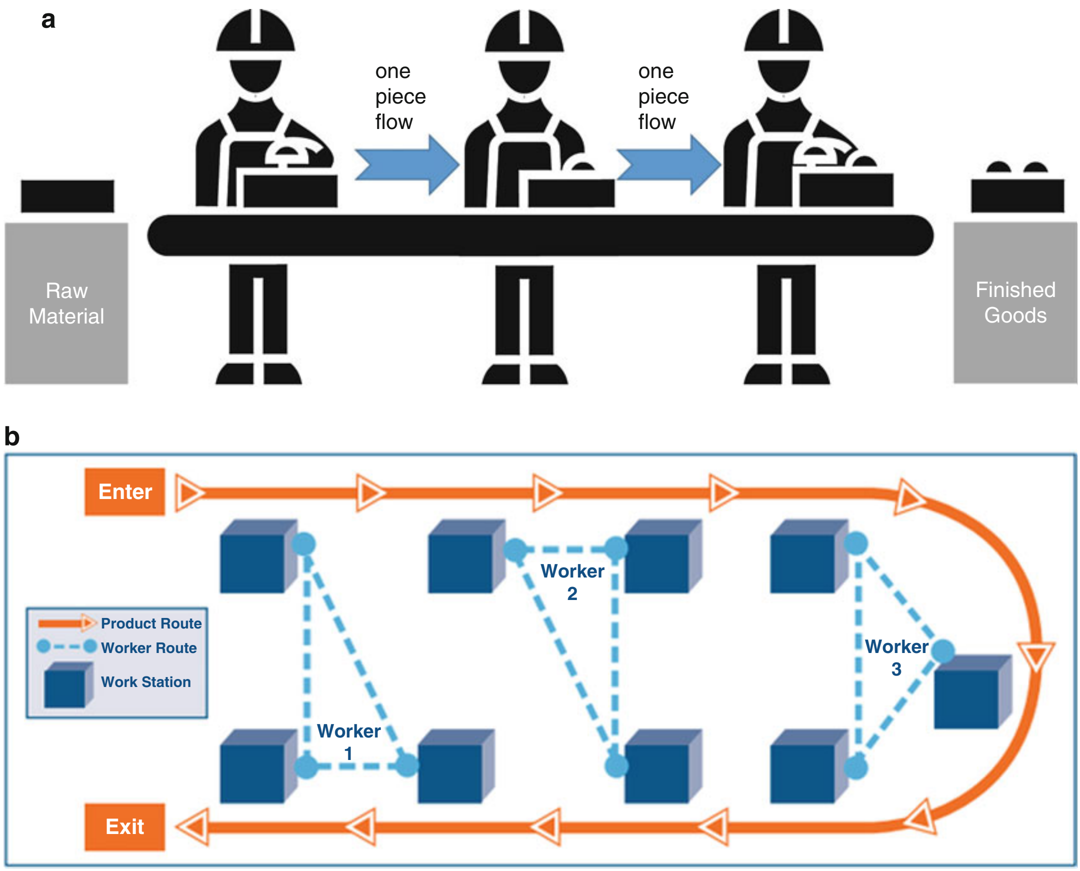
### Material Handling in One-Piece Flow

One-piece flow is a production process, or a production principle, in a production or assembly line, where an employee always transports one part from a station to the next station where it is processed, without waiting (Fig. 3a).

The advantages of one-piece flow include the following items:

- Safety: Since smaller amounts of product are moved at a time and therefore ergonomic conditions can be enhanced.
- Quality: Because the smaller a production batch is, the smaller the possible quantity of contaminated product will be, when a defect is found. With the waiting time between to workstations reduced to zero, defects are found almost instantly.
- Lead times: Because reducing inventory reduces waiting time and therefore lead times.
- Costs: Because reducing inventory improves economical indexes such as work in process (WIP).
- Flexibility: Because the ability to respond to changes in customer demand depends on the lead time. The lower the lead time is, the more flexible the factory will be.
- Productivity: Because employees spent less time looking for or transporting a product, which leaves more time available for value adding work.
- Less space for inventories: It means more workstations or facilities can be put in a factory area.

The work cell is the common way of implementing one-piece flow. Workstations are




**Material Flow, Fig. 3** (**a**) One-piece flow concept. (**b**) One-piece flow in a U-shaped cell

positioned close to each other in order to minimize transport between them.

Usually the cell is U-shaped in order to minimize also the operator movements. In this situation, there are more stations than employees.

An example is reported in Fig. 3b:

– Worker n.1 assembles the product in the first station and transports it to the second station. Transportation can be made manually or using a hand truck or a conveyor.
– Worker n.1 moves to the last two station to finish the products at the end of the route.
– Worker n.2 takes the product from worker n.1 and proceeds with his assembly operations.
– Worker n.2 moves to the third workstation together with the product and so on.

## Cross-References

▶ Assembly Line
▶ Logistics

## References

Arzet H (2005) Grundlagen des one piece flow, Leitfaden zur Planung und Realisierung von Mitarbeitergebundenen Produktionssystemen [Fundamentals of one-piece-flow. A guideline for the planning an realization of production systems]. Rhombos-Verlag, Berlin

Dini G (2012) Sistemi Integrati di Produzione: dal Controllo Numerico al Computer Integrated Manufacturing. TEP, Pisa (in Italian)
Groover MP (2008) Automation, production systems and computer integrated manufacturing, 3rd edn. Prentice Hall, Upper Saddle River
Liker JK (2004) The Toyota way: 14 management principles from the world's greatest manufacturer. McGraw-Hill, New York
Ohno T (1993) Das Toyota-Produktionssystem [Introduction to the Toyota Production System]. Campus, Frankfurt
Scharf P, Kissing A (2007) One-Piece Flow – Ein Vielseitiges Konzept für die Industrielle Serienmontage [One Piece Flow, a Versatile Concept for Series Assembly in Industry]. Industrie Manag: Zeitschrift für Industrielle Geschäftsprozesse 23:35–38
Sekine K (1992) One-piece flow: cell design for transforming the production process. Productivity Press, Cambridge
Shingo S (1989) A study of the Toyota Production System. Productivity Press, Chatswood
Womack JP, Jones DT (2006) Lean solutions: Wie Unternehmen und Kunden Gemeinsam Probleme Lösen [Lean solutions: how companies and customers can create value and wealth together]. Campus, Frankfurt

## Material Handling

▶ Material Flow

## Material Recovery

▶ Recycling

## Material Removal Processes

▶ Cutting, Fundamentals

## Material Supply

▶ Feeding

## Material Transfer

▶ Logistics

## Material Transport

▶ Handling

## Matrix

▶ Bonding Materials for Abrasive Tools

## MD

▶ Molecular Dynamics
▶ Molecular Dynamics for Cutting Processes



## Measurement Accuracy

▶ Accuracy

## Measurement Device

▶ Sensor (Assembly)

## Measurement Engineering

▶ Metrology

## Measurement Error

▶ Error

## Measurement System Analysis

Robert Schmitt[1] and Marcin Bauza[2]
[1]Laboratory for Machine Tools and Production Engineering (WZL), RWTH Aachen University, Aachen, Germany
[2]Carl Zeiss Industrial Metrology, Maple Grove, MN, USA

### Synonyms

Measurement system capability analysis; MSA

### Definition

According to international standards, m*easurement system analysis* is defined as "a series of studies that explains how a measurement system performs" (ISO 13053-2 2011) and consists of "a set of methods used to evaluate the uncertainty of a measurement process under the range of conditions in which the process operates" (ISO 22514-1 2014).

[The following is added in the definition of "measurement system" since it is not available in the encyclopedia: A *measurement system* is a "collection of operations, procedures, devices and other equipment, software, and personnel used to assign a value to the characteristic being measured" (ISO/TR 14468 2010).]

### Theory and Application

#### Introduction

Due to the fact that all measurements contain errors, it is impossible to determine the exact variation of a production process. The observed process variation is always the superposition of the production process variation (part variation) and the measurement process variation (Fig. 1).

Understanding and managing the measurement process variation, better known as "measurement error" or "measurement uncertainty" ("Error"), is therefore an important function in process control and process improvement (Montgomery 2012). Having capable measurement processes ensures the validity of acquired data and reduces the risk of erroneous decisions, like scrapping parts which are within the specification or delivering or processing parts which are outside of specification. Hence most of modern quality management systems demand capable measurement processes (*ISO 9001*; *ISO 10012*).

Excerpt from paragraph 4.11.1 ISO 9001:

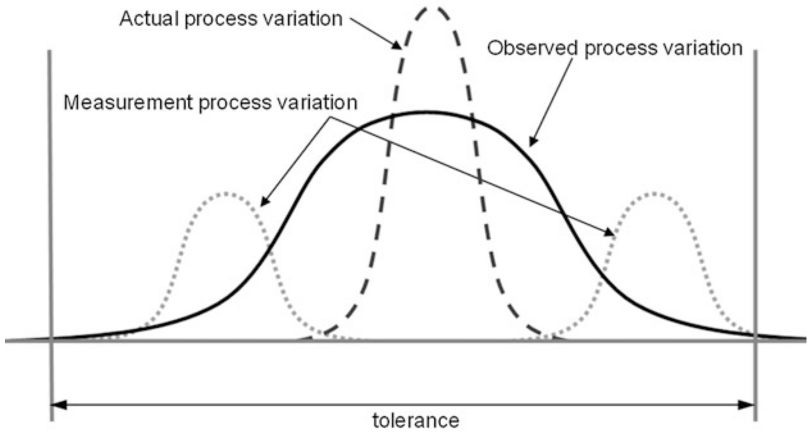
Inspection, measuring and test equipment shall be used in a manner which ensures that the measurement uncertainty is known and is consistent with the required measurement capability.

The purpose of a measurement system analysis is to determine the capability of the measurement process as well as determining its sources of variation and its behavior within the range of application. It is often used as an effective way of selecting a measurement process and equipment (instruments, gauges) and provides a basis for comparing and reconciling differences in measurements (ISO 22514-1 2014). The MSA is an important element of Six Sigma methodology and of other quality management systems (ISO 13053-2 2011).

#### Sources of Variation

A measurement system analysis usually aims at isolating and evaluating the following sources of variation of the measurement process (AIAG 2010; Dietrich and Schulze 2011, VIM (JCGM 200:2012 (2012))); see Fig. 2:

- **Systematic measurement error**
  (or bias, "Error," "Accuracy"): Systematic difference between a measurement and a reference value.
- **Repeatability**
  ("Precision"): Variation of measurements due to instrument error.
- **Reproducibility:**
  Variation resulting from external sources such as inspectors, measurement method, setup, and environmental fluctuations over time.




**Measurement System Analysis, Fig. 1** Influence of the measurement process variation on the observed process variation

- **Linearity:**
  Change of precision and accuracy of the measurement system over the expected range of the measurement.
- **Stability:**
  Change in accuracy of the measurement system over time.
- **Accuracy:**
  Accuracy is a qualitative term referring to whether there is agreement between a measurement made on an object and its true (target or reference) value (NIST).

## Methods

Measurement system studies are often divided into three different types (*ISO 22514–1*; AIAG 2010):

- A type 1 study for determining systematic errors
- A type 2 study for determining repeatability and reproducibility (gauge R&R study)
- A particular type 2 study, often called type 3, for determining repeatability where no inspector influence is present (gauge R study)

### Type 1 Study (Systematic Error)

In order to determine the systematic error of a measurement system, a reference part with a known reference value is measured multiple times (typically $n > 10$) in a short period of time. The mean of the measurement values minus the reference value serves as an indicator for the bias of the gauge (AIAG 2010).

### Type 2 Study (Gauge R&R Study)

The standard method for assessing the measurement system's precision is a so-called gauge repeatability and reproducibility study (gauge R&R study) (AIAG 2010).

For the gauge R&R study, a certain number of parts (typically 10) are measured several times (typically 2–3 times) by different inspectors (typically 2–3, Fig. 3). The results are analyzed using analysis of variance (ANOVA) or range methods, by which the overall variance can be decomposed into components associated with different sources of measurement variation (repeatability for one inspector, reproducibility between inspectors, part-to-part variation).

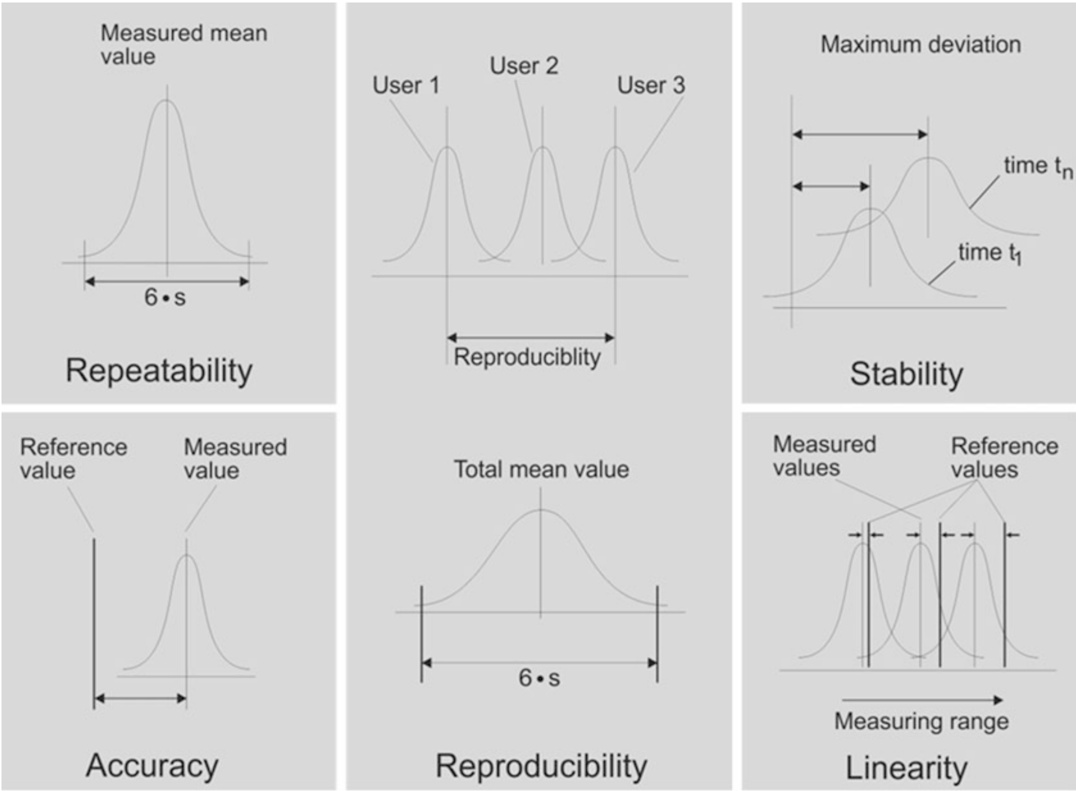
The **repeatability** is determined by evaluating multiple measurements of the same part, effectively quantifying the variability in a measurement system resulting from the gauge itself (Smith et al. 2007). Using the range method, the repeatability (or equipment variation) is calculated with

$$EV = K_1 \cdot \overline{\overline{R}}$$

$$\overline{\overline{R}} = \frac{1}{l} \cdot \sum_{i=1}^{l} \overline{R_i}$$

[$K_1$ depends on the number of repetitions and the number of inspectors; see AIAG (2010).]

The reproducibility is determined from the variation created by different inspectors measuring a part several times each, effectively quantifying the




**Measurement System Analysis, Fig. 2** Characteristics of measurement systems (Source: AIAG 2010)

variation in a measurement system resulting from the operators of the gauge and environmental factors. Using the range method, the reproducibility (or inspector variation) is calculated with

$$AV = \sqrt{(K_2 \cdot x_{\text{Diff}})^2 - \left(\frac{EV^2}{n \cdot m}\right)}$$

$$\bar{x}_{\text{Diff}} = \max\{\text{range}(\overline{x_i})\}$$

[$K_2$ depends on the number of repetitions and the number of inspectors; see AIAG (2010).]

The "total gauge R&R" is the combination of the estimated variations from repeatability and reproducibility.

$$GRR = \sqrt{EV^2 + AV^2}$$

The result of a gauge R&R study is the so-called %GRR value, which is the quotient of the GRR value and either a measure of process variation or the specification tolerance $T$:

$$\%GRR_T = 100 \cdot \frac{6 \cdot GRR}{T}$$

A commonly accepted threshold for the capability of a measurement system is a % GRR value of 10% or lower (AIAG 2010). For measurement systems which are already in use, a %GRR value of up to 30% may be accepted.

### Type 3 Study (Gauge R Study)

The type 3 study is a special case of the type 2 study and is suited for measurement systems which are not subject to influence of inspectors (e.g., automatic gauges). Instead of determining both the repeatability and reproducibility, only the repeatability is analyzed (hence the name: gauge R study). For the

| Part | Inspector A 1.test | 2.test. | 3.test. | Range | Inspector B 1.test. | 2.test. | 3.test. | Range | Inspector C 1.test. | 2.test. | 3.test | Range |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 34 | 45 | 37 | 11 | 43 | 32 | 36 | 11 | 35 | 26 | 31 | 9 |
| 2 | 56 | 44 | 59 | 15 | 49 | 37 | 45 | 12 | 46 | 43 | 47 | 4 |
| 3 | 6 | 19 | 14 | 13 | 17 | 5 | 18 | 13 | 10 | 16 | 12 | 6 |
| 4 | 50 | 55 | 48 | 7 | 54 | 54 | 51 | 3 | 51 | 55 | 56 | 5 |
| 5 | 33 | 17 | 21 | 16 | 24 | 18 | 21 | 6 | 25 | 11 | 23 | 14 |
| 6 | 36 | 42 | 43 | 7 | 45 | 32 | 37 | 13 | 36 | 32 | 31 | 5 |
| 7 | 61 | 53 | 59 | 8 | 58 | 62 | 57 | 5 | 57 | 61 | 57 | 4 |
| 8 | 12 | 31 | 16 | 19 | 15 | 23 | 11 | 12 | 19 | 27 | 12 | 13 |
| 9 | 55 | 42 | 52 | 13 | 48 | 59 | 51 | 11 | 47 | 42 | 40 | 7 |
| 10 | 38 | 49 | 47 | 11 | 47 | 31 | 42 | 16 | 37 | 39 | 38 | 2 |
| Σ | 381 | 397 | 396 | 120 | 400 | 353 | 359 | 102 | 363 | 352 | 347 | 69 |

| | Inspector A | Inspector B | Inspector C |
|---|---|---|---|
| | 381 | 400 | 363 |
| Σ | 396 | 359 | 347 |
| $\bar{x}$ | $\bar{x}_A$ = 39.1 | $\bar{x}_B$ = 37.1 | $\bar{x}_C$ = 35.4 |
| $\bar{R}$ | $\bar{R}_A$ = 12.0 | $\bar{R}_B$ = 10.2 | $\bar{R}_C$ = 6.9 |

$$\bar{x}_i = \frac{1}{n\,m}\sum_{k=1}^{n}\sum_{j=1}^{m} x_{k,j}(i)$$

$$\bar{R}_i = \frac{1}{m}\sum_{j=1}^{m} R_j$$

i : index Inspector
j : index part
k : index test
l : number of Inspectors
m : number of parts
n : repetitions by inspectors

**Measurement System Analysis, Fig. 3** Example test design in a standard gauge R&R study (Source: Pfeifer and Schmitt 2010)

study a larger number of parts (typically 25) are measured several times (typically 2–3). The repeatability is evaluated in the same way as in the gauge R&R study by calculating the equipment variation value (*EV*). Since there is no influence from inspectors, the *AV* value is set to 0.

Limitations of the standard studies:

It is crucial for a standard gauge R&R study that parts can be measured more than once. If repeated measurements on a single part are not possible, e. g., in destructive measurements, it is impossible to differ between the variation of the measurement system and the part-to-part variation.

## Additional Studies

In addition to the type 1–3 studies, a measurement system analysis can be completed by one or more of the following studies:

Resolution

As a first step of the measurement system analysis, it is advisable to check for the gauge resolution (cross-reference resolution). If the smallest incremental change that a gauge is able to detect is too large, typically greater than 5–10% of the tolerance zone, the measurement system is not capable (AIAG 2010; Dietrich and Schulze 2011).

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Linearity

The linearity of a measurement system is analyzed by measuring multiple reference parts covering the operating range of the gauge. By evaluating the average bias for each part and fitting a line and a confidence band through the data points, one can conduct a test for the linearity of the measurement system (AIAG 2010).

Stability

The stability of a measurement system is obtained by measuring the same reference part over an extended time period and by plotting it in a control chart (AIAG 2010). The stability can then be evaluated using standard control chart analysis.

Attribute Gauge Studies

Adopted methods have to be applied for attributive and destructive measurements. See AIAG (2010), Smith et al. (2007), or Montgomery (2012) for further information.

### Historical Background

In the past, missing instructions for practical implementation of measurement system analysis have led to a company-specific standards and branch-specific guidelines. In 1992, the Automotive Industry Action Group (AIAG) began to formalize methods for a measurement system analysis in the automotive industry with its publication of a *Measurement System Analysis Reference Manual* (AIAG 1992). Since then it has become a de facto standard not only in the automotive industry but in the entire manufacturing industry. The guideline is currently available in its fourth edition, which was published in 2010 (AIAG 2010).

## Cross-References

- ▶ Accuracy
- ▶ Error
- ▶ Measurement Uncertainty
- ▶ Metrology
- ▶ Precision

## References


Automotive Industry Action Group (AIAG) (1992) QS 9000: measurement systems analysis. Chrysler Group LLC/Ford Motor Company/General Motors Corporation, Michigan

Automotive Industry Action Group (AIAG) (2010) QS 9000: measurement systems analysis, 4th edn. Chrysler Group LLC/Ford Motor Company/General Motors Corporation, Michigan

Dietrich E, Schulze A (2011) Measurement process qualification. Gauge acceptance and measurement uncertainty according to current standards. Hanser, Munich

ISO 10012 (2003) Measurement management systems – requirements for measurement processes and measuring equipment. International Organization for Standardization, Geneva

ISO 13053-2 (2011) Quantitative methods in process improvement – six sigma – part 2: tools and techniques. International Organization for Standardization, Geneva

ISO 22514-1 (2014) Statistical methods in process management – capability and performance – part 1: general principles and concepts. International Organization for Standardization, Geneva

ISO 9001 (2015) Quality management systems – requirements. International Organization for Standardization, Geneva

ISO/TR 14468 (2010) Selected illustrations of attribute agreement analysis. International Organization for Standardization, Geneva

JCGM 200:2008 (2008) International vocabulary of metrology: basic and general concepts and associated terms (VIM). http://www.bipm.org/en/publications/guides/vim.html. Accessed 25 Apr 2014. Bureau International des Poids et Mesures, Sèvres

JCGM 200:2012 (2012) International vocabulary of metrology: basic and general concepts and associated terms (VIM). Bureau International des Poids et Mesures, Sèvres

Montgomery DC (2012) Introduction to statistical quality control. Wiley, New York

Pfeifer T, Schmitt R (2010) Fertigungsmesstechnik [metrology], 3rd edn. Oldenbourg Wissenschaftsverlag, München (in German)

Smith RR, McCrary SW, Callahan RN (2007) Gauge repeatability and reproducibility studies and measurement system analysis: a multimethod exploration of the state of practice. J Qual Technol 23(1):1–11


## Measurement System Capability Analysis

▶ Measurement System Analysis

## Measurement Technique

► Metrology

## Measurement Uncertainty

Han Haitjema
Mitutoyo RCE, Best, The Netherlands
KU Leuven, Department of Mechanical Engineering, Leuven, Belgium

### Synonyms

Uncertainty of measurement

### Definition

A nonnegative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used (Source: JCGM 200:2012 (2012) (VIM)).

### Theory and Application

#### Introduction

Few subjects have generated so much debate in the recent decennia as the concept "uncertainty," better specified as "measurement uncertainty." The need for a harmonized approach came from industry, standardization organizations, accreditation organizations, national metrology institutes, etc.

Historically, measurement uncertainty is closely related to the progress of science and adoption/rejection of theories. From the industrial side, there is the fitting of products or, if that cannot be done directly, specifying products and testing whether these specifications are met.

On the other hand, there is the field of statistics, taking samples out of a – limited or unlimited – range of possible outcomes and estimating what the distribution will be behind the outcomes when a limited set – down to one – of outcomes is available.

#### Basic Documents

Where in the past – and still – physicists are taught "correct for systematic errors and add all random errors (i.e., standard deviations) quadratically," it was not uncommon that mechanical engineers had as a rule "add all maximum errors to minimize the risk." Nowadays, it is agreed that "systematic" and "statistical" errors are not so essentially different and that a harmonized approach is possible. The approach as outlined in the "GUM" (GUM 1995; JCGM 100:2008 2008) is most generally agreed and available. This document has a supplement 1 (JCGM 101:2008 2008) that looks less basic from the title; but, in fact, this second part is considered the most fundamental basis. The difference is that in supplement 1, uncertainty is basically treated as the propagation of uncertainty distributions, rather than uncertainties, and that these can be simulated by Monte Carlo methods.

The approach of these documents may look complicated, and for this reason, several hands-on documents have appeared that claim to have a more practical approach. Typical examples are the EA-document EA-4/02 M (2013) and the "PUMA" approach explained in ISO 14253-2 (2011).

#### Basic Method

In practice, the precise uncertainty distribution, correlation, and degrees of freedom considerations may not be too relevant, and we will omit these aspects from now on. With the risk of simplifying things too much and without the pretention of giving a definite simplified approach, the basic method can be summarized as follows:

In general, a measurement result $y$ is a function of $n$ input quantities $x_i$ ($i = 1,2,\ldots n$). These input quantities can be measured values, known constants, etc. This leads to the general functional relationship, known as the "model function" (EA-4/02 M 2013):

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$$y = f(x_1, x_2, \ldots x_n) \tag{1}$$

The model function incorporates the measurement and the calculation procedure. It can be an analytical function, but also a complicated, iterative, computer algorithm. The measurement data $x_i$ can be grouped into two categories, depending on the way they, and their uncertainty, are obtained:

(a) Quantities where the value and its uncertainty are directly obtained from the measurements
(b) Quantities where the uncertainties are obtained from other sources, such as calibration data, used material constants, previous measurements.

However, this grouping does not influence the uncertainty evaluation; it is just essential that a standard uncertainty $u_{xi}$ is attributed to any influencing quantity $x_i$.

The quantity $Y$ is best approximated by using the measurement result $y$, calculated from best approximations for $X_i$: $x_i$, which are usually the measured data, in Eq. 1.

Now, the uncertainty $uy$ can be written as:

$$u_y^2 = \sum_i \left( \left[ \frac{\partial y}{\partial x_i} \right]_y \right)^2 \cdot \langle \Delta_i^2 \rangle + 2 \cdot \sum_{i<j} \left[ \frac{\partial^2 y}{\partial x_i \cdot \partial x_j} \right] \cdot \langle \Delta_i \cdot \Delta_j \rangle \tag{2}$$

where $\Delta_i$ and $\Delta_j$ are the deviations from their true value $X_i$ of $x_i$ and $x_j$, respectively; and $<>$ denotes the average over a large ensemble. The squared expected deviation of $x_i$ from its real value $<\Delta_i^2>$ is known as the variance, which is the square of the standard uncertainty $u_i$. So $u_i^2 = <\Delta_i^2>$. The product $<\Delta_i \cdot \Delta_j>$ is known as the covariance of the deviations in $x_i$ and $x_j$. In the case of uncorrelated measurement data $x_i$ and $x_j$, Eq. 2 reduces to:

$$u_y^2 = \sum_i \left( \left[ \frac{\partial y}{\partial x_i} \right]_y \right)^2 \cdot u_{x_i}^2 \tag{3}$$

This implies that the expected effects of all influencing factors on the measurement result y are added quadratically. It is common, e.g., in EA-document EA-4/02 M (2013), to set up this calculation in the form of a table as it is shown in Table 1. In the table, we denoted the contributions from the individual influencing factors with $\Delta_i$ as these deviations can be both positive and negative. They can also be written as $u_i$ with $u_i = |\Delta_i|$; where all contributions are squared in the end, this makes no difference.

Such a table is known as an "uncertainty budget." It gives a rapid overview of all influencing factors and their influences. From this, it can easily be seen which factors can best be decreased in order to achieve a lower (better) final uncertainty. For laboratories seeking accreditation, it is in general compulsory that uncertainty budgets are made for every quantity one is accredited for.

## Monte Carlo Method

In the case of many measurement data and complicated measurements, it can be impracticable to set up a full uncertainty budget which includes all quantities. Instead of varying the quantities one by one, as it is shown in Table 1, one can vary all parameters simultaneously. As the sign of all deviations is not determined, the different influencing factors can both amplify and weaken each other. If we define a random number $r$ as having an average of 0 and a standard deviation of 1, so $<r> = 0$, $<r_i \cdot r_j> = \delta_{i,j}$ (d being the Kronecker $\delta$-symbol with $\delta_{ij} = 1$ for $i = j$, otherwise 0) and $<r^2> = 1$, where $<>$ denotes the average over a large ensemble, then we can simulate a measurement result by varying all input quantities at a time, as following:

$$y_r = y(x_1 + r_1 \cdot u(x_1), x_2 + r_2 \cdot u(x_2), \ldots, x_N + r_N \cdot u(x_N)) \tag{4}$$

The average of $y_r$ is the expected value of $y$, and the standard deviation of $y_r$ is the standard deviation of $y$ that can be used as a measure of the uncertainty. Proofs of this are given by Haitjema (2011).

**Measurement Uncertainty, Table 1** General form of an uncertainty budget

| Quantity $X_i$ | Value of quantity $x_i$ | Standard uncertainty $u(x_i)$ | Sensitivity coefficient $c_i = \frac{\partial y}{\partial x_i}$ | Contribution to standard uncertainty in $y$ $c_i \cdot u(x_i) = \Delta_i(y)$ |
|---|---|---|---|---|
| $X_1$ | $x_1$ | $u(x_1)$ | $c_1$ | $\Delta_1(y)$ |
| $X_2$ | $X_2$ | $u(x_2)$ | $c_2$ | $\Delta_2(y)$ |
| : | : | : | : | : |
| $X_N$ | $x_N$ | $u(x_N)$ | $c_N$ | $\Delta_n(y)$ |
| $Y$ | $y$ | | *Total*: | $u(y) = \sqrt{\Delta_1^2 + .. + \Delta_n^2}$ |

The number of simulations ($K$) needed depends on the purpose of the simulations. If one wants to simulate different distributions for each quantity, and consider the final uncertainty distribution, then some hundreds of simulations are needed. For a Gaussian distribution, an estimate for the "standard deviation in the standard uncertainty" $s(u)$ is given by:

$$s(u) = \frac{u}{\sqrt{2K - 2}} \quad (5)$$

This means that if one aims to have a "simulation" uncertainty of about 10 % of the estimated uncertainty, some 50 simulations must be carried out ($K = 50$). Herewith, it must taken into consideration that out of their nature, the uncertainties which act as input for the simulations are seldom estimated much better than 30 %.

This method of calculation of uncertainties has the following characteristics and possibilities:

- The uncertainty distribution can be determined where different input quantities have different distributions
- One can choose either to determine the standard uncertainty or to calculate the 95 % confidence interval. In the latter case, one must consider the distribution of some hundreds of simulations.
- The method accounts for higher-order terms if the system formula contains products of terms with nominal values of 0.
- The reality can well be approximated by keeping an "unknown systematic error" constant in each simulation, but vary it between simulations. Examples are probe diameters, temperatures and temperature gradients, calibration-uncertainties of material measures, etc.
- A known systematic error which is not corrected can be simulated with its value taken as the standard uncertainty and the random number $r = \pm 1$. This can be considered as a bi-modal distribution (Tyler Estler 1999).
- Correlations between quantities can be simulated by correlating the used random numbers.

These characteristics make the Monte Carlo simulation method, a potential tool for estimations of uncertainties which are not possible when using the mainstream GUM uncertainty budget. Especially for complicated measurements, such as carried out by a CMM, or by form measuring instruments, it is about the only feasible method. Some earlier publications on this subject in dimensional metrology were given by Schwenke (1999; Schwenke et al. 2000). More specifically about CMMs, a European research project was carried out (Trapet et al. 1999). As a follow-up of this, several participants continued the research (Balsamo et al. 1999; van Dorp et al. 2001). This research was summarized by Wilhelm et al. (2001). The general concept of using Monte Carlo method in uncertainty evaluation is described by Cox et al. (2001).

## Uncertainty and Confidence Intervals

Uncertainty can be expressed as a standard uncertainty $u(y)$. The standard uncertainty can be multiplied by a number $k$ such that it gives a confidence interval for the measurand $Y$. Then the probability of $Y$ to be in the region $[y - k \cdot u(y); y + k \cdot u(y)]$ can be expressed as a percentage, and the region

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is called the confidence interval. With some approximations and the assumption of a Gaussian distribution, it can be stated that taking $k = 2$ will generate a confidence interval of approximately 95 %.

It can be discussed what is most useful: just the standard uncertainty or a confidence interval. As an end result, the confidence interval is most useful for the user; however, if the uncertainty is to be used in other uncertainty calculations (i.e., $y$ becomes one of the quantities $x$ in a further measurement process), the standard uncertainty is more useful.

## Use of Uncertainty

It is generally stated that a measurement result without indication of uncertainty has no value. However, how and for what this uncertainty is useful or can be used may vary. We give a few possibilities here:

### Testing of Scientific Theories

In order to prove that a theory must be wrong or to demonstrate the superiority of the one theory against the other, it is the uncertainty in the measurement that enables a judgment. For a recent example, an experiment can give as a result that neutrinos travel faster than the speed of light, but the real scientific debate starts if their speed is faster than the speed of light when the measurement uncertainty is taken into account with a significant confidence interval.

### Testing Against Specifications

If the geometry of a product must satisfy certain specifications, it must do so including its uncertainty interval. If the uncertainty interval overlaps the specification limit, there is a problem. The probability of this problem can be reduced by reducing the uncertainty, but it cannot be eliminated. In ISO 14253-1 (2013), it is stated that the uncertainty is always a disadvantage for the interested party. So a manufacturer wanting to sell his instrument must show that this instrument can meet the specification including the measurement uncertainty interval. For a customer who wants to complain that a machine is outside its specification, the measurement result including its confidence interval must be outside the specification limits.

### Calibration of Standards and Measurement Instruments

The two actions mentioned previously can only be carried out using calibrated instruments and standards. The uncertainty can only be calculated if the uncertainty of these calibrations is known.

## Uncertainty and Traceability

Uncertainty and traceability appear to be different concepts, but, in fact, they are identical twins. If a measurement is traceable, an uncertainty budget can be made that includes the calibration of the reference standard. The uncertainty of this reference standard can only be properly stated if it is traceable to a primary standard. On the other hand, if no uncertainty calculation can be made, a measurement cannot be traceable, and if a measurement is not traceable, no uncertainty can be calculated as the uncertainty of the used references is not known.

## Cross-References

▶ Accuracy
▶ Calibration
▶ Error
▶ Traceability

## References

Balsamo A, Di Ciommo M, Mugno R, Rebaglia BI, Ricci E, Grella R (1999) Evaluation of CMM uncertainty through Monte Carlo simulations. Ann CIRP Manuf Technol 48(1):425–428

Cox MG, Dainton MP, Harris PM (2001) Software specifications for uncertainty calculation and associated statistical analysis. National Physics Laboratory (NPL) report CMSC 10/01. National Physics Laboratory, Teddington

EA-4/02 M (2013) Expression of the uncertainty of measurement in calibration, European co-operation for accreditation. http://www.european-accreditation.org/publication/ea-4-02-m-rev01-september-2013. Accessed 14 March 2016

GUM (1995) Guide to the expression of uncertainty in measurements. ISO, Geneva

Haitjema H (2011) Task specific uncertainty estimation in dimensional metrology. Int J Precis Technol 2:226–245

ISO 14253-1 (2013) Geometrical product specifications (GPS) – inspection by measurement of workpieces and measuring equipment, part 1: decision rules for proving conformance or non-conformance with specifications. ISO, Geneva

ISO 14253-2 (2011) Geometrical product specifications (GPS) – inspection by measurement of workpieces and measuring equipment. Part 2: guidance for the estimation of uncertainty in GPS measurement, in calibration of measurement equipment and in product verification. ISO, Geneva, 1998

JCGM 100:2008 (2008) Evaluation of measurement data – guide to the expression of uncertainty in measurement (GUM 1995 with minor corrections). Bureau International des Poids et Mesures

JCGM 101:2008 (2008) Evaluation of measurement data – supplement 1 to the 'Guide to the expression of uncertainty in measurement' – propagation of distributions using a Monte Carlo method. Bureau International des Poids et Mesures. http://www.bipm.org/utils/common/documents/jcgm/JCGM_101_2008_E.pdf. Accessed 14 March 2016

JCGM 200:2012 (2012) International vocabulary of metrology: basic and general concepts and associated terms (VIM). Bureau International des Poids et Mesures. http://www.bipm.org/utils/common/documents/jcgm/JCGM_200_2012.pdf. Accessed Mach 14 2016; Recent update: JCGM:200:2012

Schwenke H (1999) Abschätzung von messunsicherheiten durch simulation an beispielen aus der fertigungsmesstechnik [A simulation-based approach for the estimation of measurement uncertainties in the area of prodcution measurement technology], Thesis, PTB-F-36, Physikalisch-Technische Bundesanstalt, Braunschweig (in German)

Schwenke H, Siebert BRL, Wäldele F, Kunzmann H (2000) Assessment of uncertainties in dimensional metrology by Monte Carlo simulation, proposal of a modular and visual software. CIRP Ann 49(1):395–398

Trapet E, Franke M, Härtig F et al (1999) Development of methods and guidelines to establish traceability for measurements with coordinate measuring machines, EU project contract no. MAT1-CT94.0076, European Commision bcr information project report Applied Metrology, Directorate-General Science, Research and Development

Tyler Estler W (1999) Measurement as inference: fundamental ideas. CIRP Ann 48(2):611–631, keynote paper

van Dorp B, Delbressine FLM, Haitjema H, Schellekens PHJ (2001) Calculation of measurement uncertainty for multi-dimensional machines, using the method of surrogate data. In: Ciarlini P et al (eds) Advanced mathematical and computational tools in metrology V. World Scientific Publishing, Singapore, pp 344–351

Wilhelm RG, Hocken R, Schwenke H (2001) Task specific uncertainty in coordinate measurement. Ann CIRP Manuf Technol 50(2):553–563

## Measuring Probe

► Sensor (Assembly)

## Mechanical Joining

Dirk Landgrebe
Fraunhofer Institute for Machine Tools and Forming Technology IWU, Chemnitz, Germany

### Synonyms

Cold joining; Joining by forming

### Definition

Joining by forming refers to a range of joining methods which are used to join two or more components by local plastic deformation of at least one joining partner and/or of a joining element.

### Theory and Application

#### Overview

In general, connections generated by forming are created by local plastic deformation of the workpiece and/or the fastener, generating a positive and nonpositive connection between the parts. In addition, residual stresses caused by the joining process can occur in the parts to be joined as well as in the joining element, which can result in traction. Due to the combination of positive and nonpositive locking, high connection strength of the joint is possible (Budde and Pilgrim 1995).

In contrast to welding technologies, usually no heat input and no melting of the materials are required. Accordingly, sometimes this joining method is also referred as "cold joining." Table 1 summarizes the general advantages and disadvantages of joining by forming processes.

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**Mechanical Joining, Table 1** General advantages and disadvantages of joining by forming (similar to Böllinghaus et al. 2009)

| Advantages | Disadvantages |
|---|---|
| Metallic and nonmetallic materials, material combinations, as well as different material thicknesses can be joined<br>Higher tolerable fatigue load compared to, e.g., welded joints<br>No abrupt collapse<br>Simple quality control mechanism<br>High process reliability<br>High economic efficiency (small investment cost of machinery, pre- and posttreatment of workpieces rarely necessary)<br>Materials with surface coatings can be joined without additional expenditure<br>No thermal structural transformation of parts and therefore neither distortion, residual stress, or embrittlement<br>Low energy requirements<br>Very good environmental behavior (neither emission nor pollution) | Only lap joints possible<br>Applications are limited if accessibility is required from two sides<br>Individual tool geometry and parameters depending on joining task<br>Geometrical unevenness due to nature of the process<br>Usually more difficult correction and repair of improper joints<br>In case of pilot holes, cross sections are locally weakened |

Joining by forming processes can be classified differently according to the method of evaluation. At the moment there is no international standard for joining by forming processes, but a number of national classifications and publications exist such as DIN 8593–5 2003, DVS 2009, Mori et al. 2013, and Böllinghaus et al. 2009. In Mori et al., for example, only self-piercing riveting, clinching, joining by hydroforming, electromagnetic forming, and hemming are considered as joining by forming processes. Applying a wider range of consideration, joining processes which make use of, e.g., screws can be included as well. Other aspects that can be applied for systematization include:

- With or without pilot hole in one joining partner
- Single-sided or double-sided access to the joint spot
- The nature of the joint connection is point, line, or two-dimensionally
- Connection properties as detachability or strength level

The classification in Fig. 1 includes cold processes with substantial plastic deformation and plain materials (sheets, tubes, profiles). Thus, the field is focused. The majority of bolting, shaft-hub connections, wire processing, bulk metal joining (e.g., extrusion multilayer material), and special technologies (e.g., friction stir welding) is not considered.

The overview includes widely used methods of mechanical joining of sheet metal parts divided into three categories.

*Without fasteners:*
the compound is produced exclusively by plastic deformation of the parts themselves, e.g., clinching.

*With fasteners:*
technologies are based on the use of joining elements such as blind rivets.

*Functional elements:*
in the first step, nuts and studs are usually connected by forming with only one of the parts. The second joining partner is then joined with the first component by a screwing operation using the internal or external thread in the functional element, e.g., self-piercing nuts.

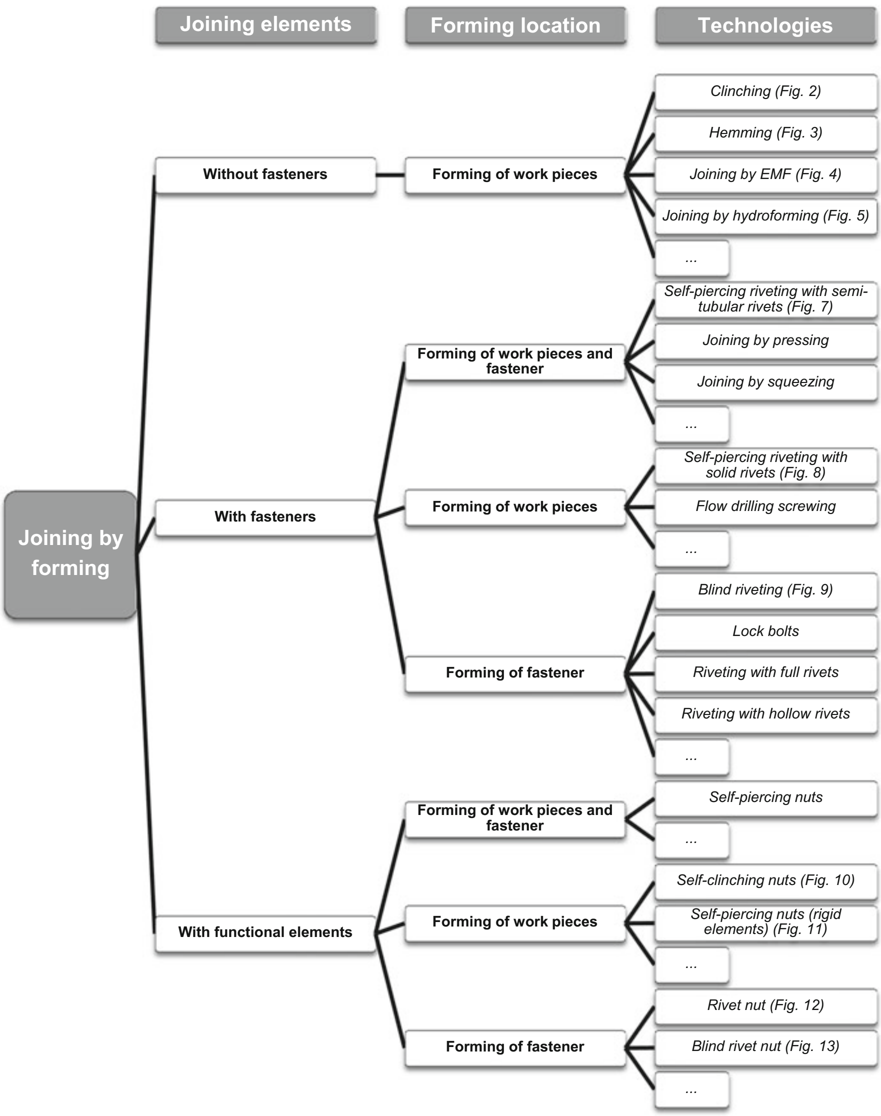
In addition to these methods, there are a number of specific joining methods that are modifications or combinations of the mentioned processes.

## Examples of Applied Mechanical Joining Processes

### Clinching

Clinching processes are widely used in various sectors such as electrical appliances, automotive industries, and white goods.

In conventional clinching the components to be joined are deformed jointly with a clinching



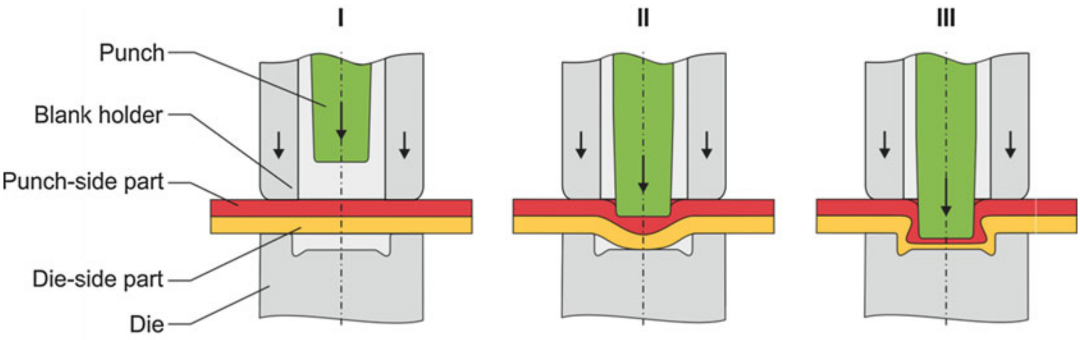

**Mechanical Joining, Fig. 1** Classification of joining by forming (similar to Riedel 2004)

punch in a contoured die. The die has a special shape that facilitates the formation of component interlocking of the punch-side part into the bottom part. The shape of the die depends on the punch diameter, the overall thickness, and the strength of the parts to be joined.

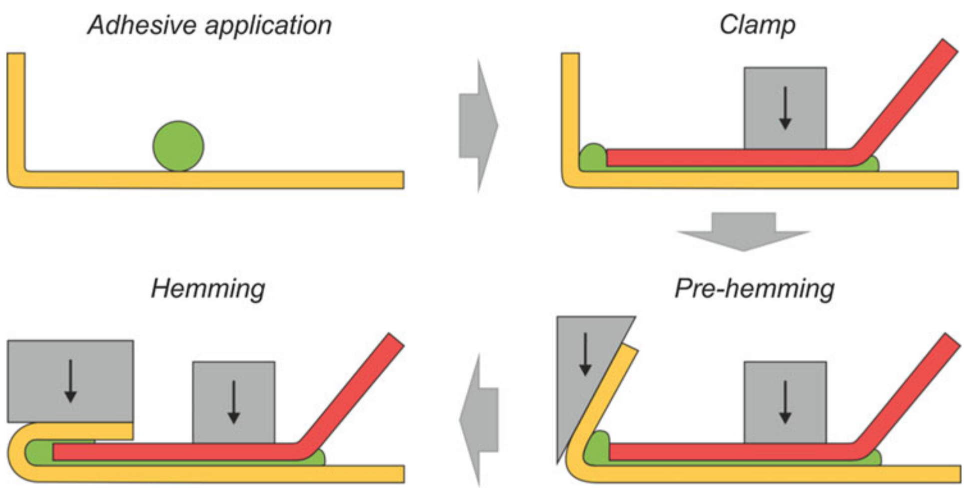
There are different variants with or without (Fig. 2) cutting the parts during the process. The die on the bottom side can be rigid and also with movable elements to support the formation of the interlocking joint. Figure 2 shows the stages of the clinching process of two sheets with a standard round clinch joint using a rigid die.

At the beginning the parts to be joined are fixed by the blank holder (Fig. 2-I). Then the punch is pressed into the parts with material being indented into the shaped die (Fig. 2-II). The connection is finally generated by reaching a final position of the punch as soon as the interlocking joint is properly formed (Fig. 2-III).

Further information about properties of possible connection joints as well as applications of




**Mechanical Joining, Fig. 2** Process stages of clinching without cutting the parts




**Mechanical Joining, Fig. 3** Process stages of hem flange bonding

clinched joints can be found, e.g., in Budde and Pilgrim (1995), Hahn and Klemens (1996), and DVS (2009).

### Joining by Hemming (Seaming)

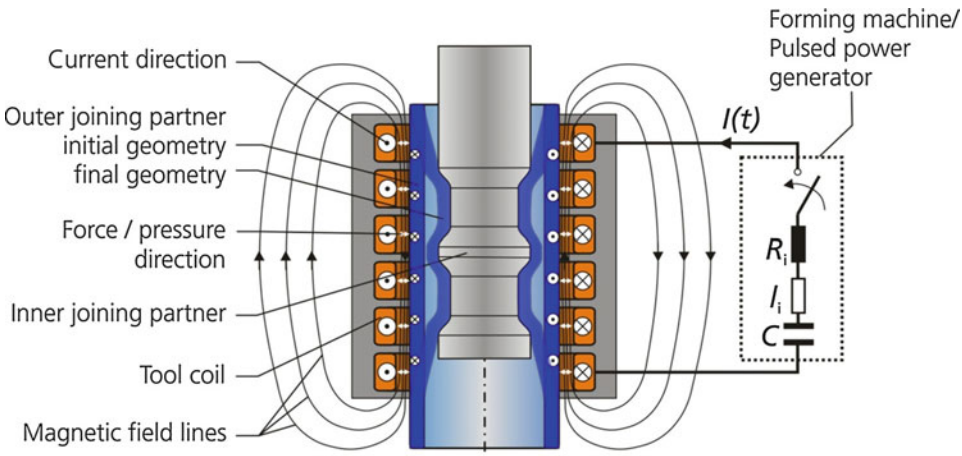
In hemming processes the edge of a metal sheet is bent in an open or closed U-shape in two or more steps. In seaming processes, two parts with U-shaped edges are pressed together, creating an interlock (DIN 8593–5 2003).

Hem flange bonding is a process for joining two sheets by combining adhesive bonding and hemming. The adhesive between the parts to be joined assures high strength of the connection and protects against corrosion. Hem flange bonding is a common process in car body construction, e.g., for doors, hoods, and tailgates. The process, shown in Fig. 3, can also be applied without adhesives (Neugebauer et al. 2010).

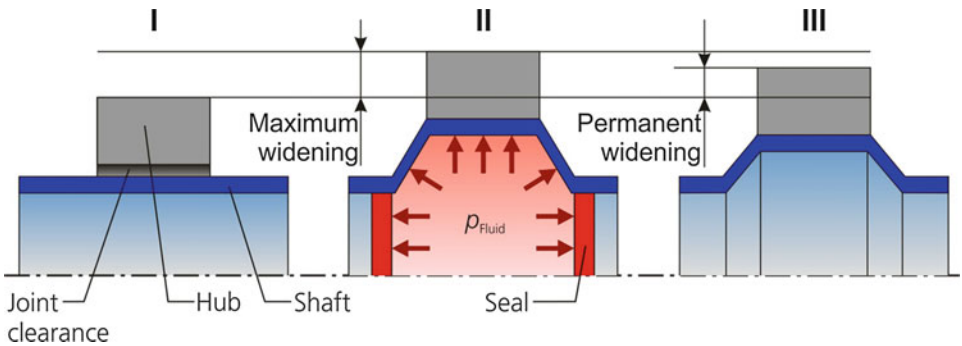
### Joining by Electromagnetic Forming (EMF)

Electromagnetic forming is a high-speed forming technology that can be applied for joining of sheet metal and profile-shaped workpieces made of electrically conductive materials (Psyk et al. 2011) (Fig. 4).

The force is applied via the energy density of pulsed magnetic fields and does not require any physical contact of tool and workpiece. As a consequence of the force application, the workpieces




**Mechanical Joining, Fig. 4** Electromagnetic joining (EMF)




**Mechanical Joining, Fig. 5** Joining by hydroforming

are accelerated up to velocities of several hundreds of meters per second, resulting in strain rates in the magnitude of up to 10.000 $s^{-1}$.

By means of EMF, similar as well as dissimilar material combinations can be connected. Thereby, the joining mechanism can be

- Interference fit, based on elastic-plastic bracing
- Form fit, based on the formation of undercuts
- Metallic bonding by cold welding

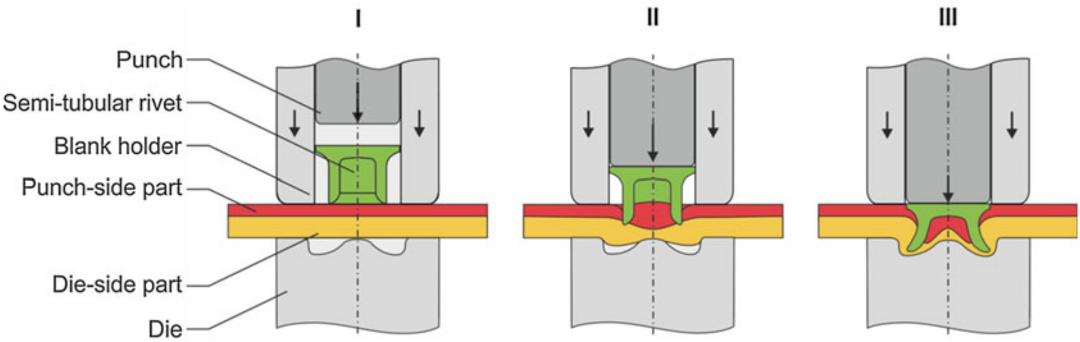
### Joining by Hydroforming

In joining by hydroforming, the connection of a tube-shaped part with an enclosing part takes place due to expansion of an inner part under the effect of internal fluid pressure (Fig. 5). Figure 5-I represents the configuration of the joint, Fig. 5-II shows the hydroforming situation, and Fig. 5-III shows the joint after releasing the fluid pressure. The type of connection can be both form and force fit.

Joining by hydroforming is applied to connect reinforcements in profiles or to join cams with a camshaft (Fig. 6). The advantages of joining by hydroforming include

- Significant reduction of weight of the component (up to 50%)
- Significant reduction of material for production (resource efficiency)
- Shortening of process chain/reduction of process steps


**Mechanical Joining, Fig. 6** Camshaft joined by hydroforming, reprinted courtesy of Fraunhofer




**Mechanical Joining, Fig. 7** Process stages of self-piercing riveting with semi-tubular rivets

### Self-Piercing Riveting with Semi-Tubular Rivets

Self-piercing riveting with semi-tubular rivets is the most important mechanical joining technique in car body manufacturing. The main application area comprises the joining of mixed compounds (e.g., steel and aluminum) and aluminum joints. Two or more parts can be joined with an overall sheet thickness in the range of 1 mm up to 9 mm. Precondition consists of two-sided accessibility of the parts to be joined, whereas pre-holes in the parts are not required. Changing joining tasks may require an adjustment of rivet length and hardness. In order to achieve better joint quality, there is a preferred setting for the joining process.

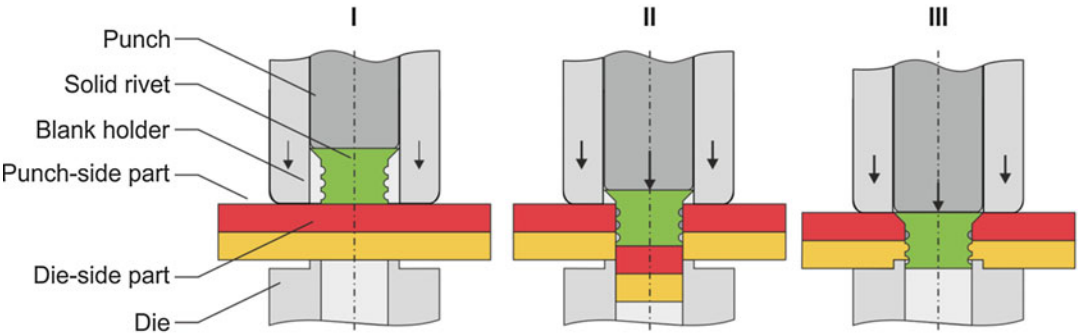
The self-piercing riveting process can be divided into three stages as shown in Fig. 7. At first, the parts and the rivet are positioned between punch, blank holder, and die (Fig. 7-I). Afterward, the punch presses the semi-tubular rivet into the parts. Due to the cutting edge of the rivet, a slug is punched out of the punch-sided part and enclosed inside the rivet (Fig. 7-II). Finally, the shape of the die causes the rivet to flare and creates an interlock, and the cavity of the die is filled with material (Fig. 7-III).

Due to the described characteristics of the plastic deformation process, there is a recommended "joining direction" for self-piercing riveting with semi-tubular rivets: the joint should first meet the hard and then the softer material, e.g., first steel and then aluminum. Accordingly, the thinner material should be on top of the thicker one. The detailed description of properties of possible connection joints as well as applications of self-piercing riveting can be found, e.g., in Voelkner et al. (1993) and in Hahn and Klemens (1996).

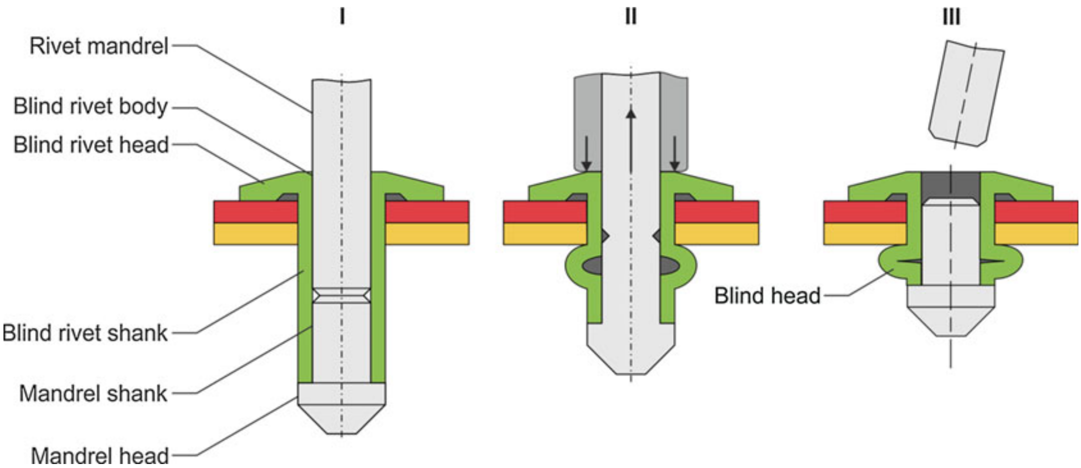
### Self-Piercing Riveting with Solid Rivets

Due to the process characteristics of self-piercing riveting with solid rivets, the geometrical unevenness on the bottom of the joint can be prevented compared to semi-tubular rivets.

At the beginning of the process, the parts are fixed between die and blank holder (Fig. 8-I). Afterward, resulting from the movement of the punch, a hole is pierced into the components by the rivet and is subsequently pressed into the parts until the countersunk head of the rivet is installed flush with the surface of the upper piece of the sheet metal (Fig. 8-II). In the third step, parts and rivet are jointly pressed against the die to indent




**Mechanical Joining, Fig. 8** Process stages of self-piercing riveting with solid rivets




**Mechanical Joining, Fig. 9** Process stages of blind riveting

the die into the lower sheet metal. As a result, material of the die-side sheet metal is pressed radially into the shaft groove of the rivet, which then creates a positive fit (Fig. 8-III).

A high level of ductility and a low level of material strength are beneficial for pressing the die-side sheet metal into the groove of the rivet. Hence, aluminum sheets are preferably arranged on the die-side in case of steel-aluminum joints.

Depending on the thickness of the parts, joining brittle materials such as casting alloys or high-strength steels is possible if the part is not positioned on the die-side.

If flatness of the bottom of the connection is not required, more connections can be joined with a single rivet length.

Similar to the process of the self-piercing riveting with semi-tubular rivets, detailed description of properties of the connection joints as well as applications can be found in, e.g., Hahn and Klemens 1996.

### Blind Riveting

Blind riveting is a very common method for joining metal sheets. Blind rivets are used to connect two or more parts. It is characteristic for blind rivets that only one-sided accessibility of the tools during the joining operation is required (e.g., connecting a sheet to a profile). A variety of constructive types and materials of blind rivets exists (DVS 2009), with the type of blind rivet being determined by the joining task. Several research projects have been carried out to investigate the joint properties (e.g., Hahn and Timmermann 2000).

The principal process stages of blind riveting are illustrated in Fig. 9. The blind rivet generally

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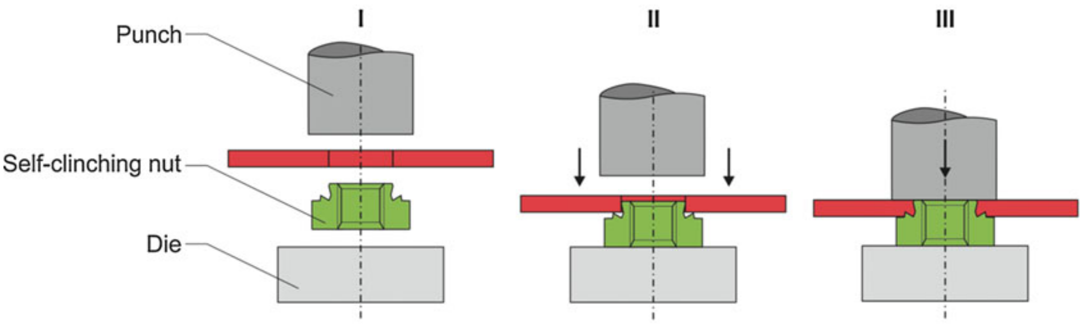



**Mechanical Joining, Fig. 10** Setting process of self-clinching nut

consists of a blind rivet body with head and shank and a mandrel. The joining process requires a hole at the joint position, which is usually drilled through the parts since the components lay on top of each other precisely and tight tolerances of the holes diameter can be achieved. In the first step of the riveting process, the blind rivet is inserted into the hole (Fig. 9-I) until the head is positioned flush on the upper part. In the second process step, the riveting tool applies a tensile force on the rivet mandrel supporting itself on the blind rivet head and shaping the blind head (Fig. 9-II). The riveting tool supports itself on the rivet head. The size of the closing force is limited in the last process step (Fig. 9-III) by the mandrel break at the predetermined breaking point of the rivet mandrel. The ruptured mandrel shank is disposed.

The components to be joined are clamped between the blind rivet head and the blind head. Depending on the design of the blind rivet, a clearance remains between the hole and the rivet shank during the setting process, or the clearance will be compensated due to an expanding blind rivet shank.

### Mechanical Joining Process Using Nuts and Studs

The term functional element summarizes carriers of formed threads. Functional elements consist of a functional portion (thread) and a fastening portion. A distinction is made concerning nut and bolt elements (with or without thread) and hole- and thread-forming screws (DVS 2009). A classification of the functional elements can be carried out with regard to design, accessibility to the joint location, and preparation of the joint. Furthermore, it can be differentiated between the forming of the shape-section and/or the component material, as proposed in Fig. 1.

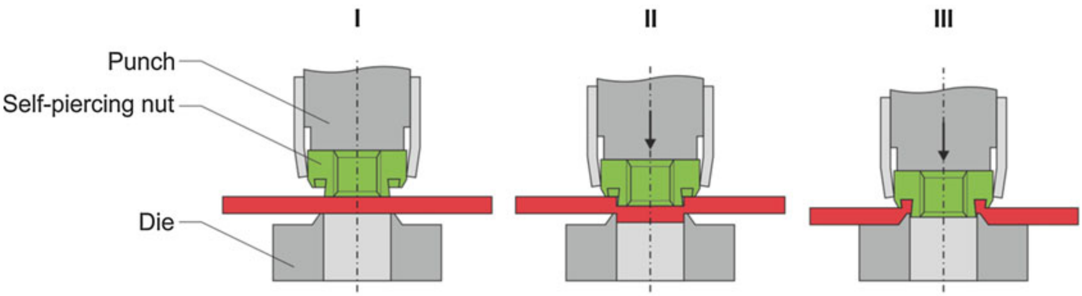
To ensure the process capability of the functional elements, components and assembly equipment must be specially designed.

Self-clinching nuts (Fig. 10) and studs are not deformed during the setting process. The joint is created by forming the workpiece material. The workpiece needs to be pre-holed.

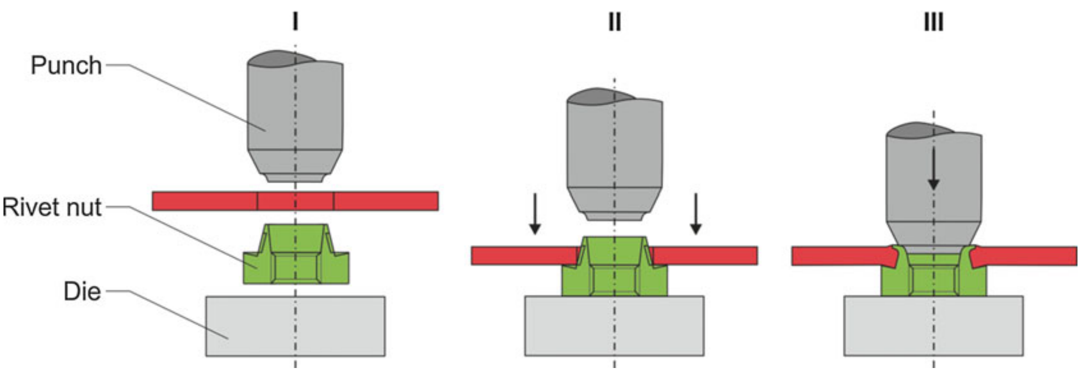
Self-piercing nuts and studs are set into the sheet metal without pre-manufactured holes. In the following the joining process will be explained based on the setting of self-piercing nuts. After positioning the nut on the workpiece (Fig. 11-I), the sheet metal is pierced as the punch collar of the self-piercing nut functions as a punch (Fig. 11-II). The sheet is placed on a die with a hole through which the slug is discharged. After the successful piercing operation, a contour on the die is pressed into the sheet, thus filling the clinch area of the nut with material (Fig. 11-III). The process creates an interference lock and force closure connection between workpiece and nut. This connection enables the screwing of threaded elements into the assembly.

Riveted functional elements (Fig. 12) are joined by forming the rivet section and/or the hole wall surrounding with the rivet section in a pre-holed component.

When using blind rivet nuts and bolts (Fig. 13), a pre-hole is necessary for the application. The blind rivet nuts and bolts can be set from one side with a processing tool by forming a defined element section.

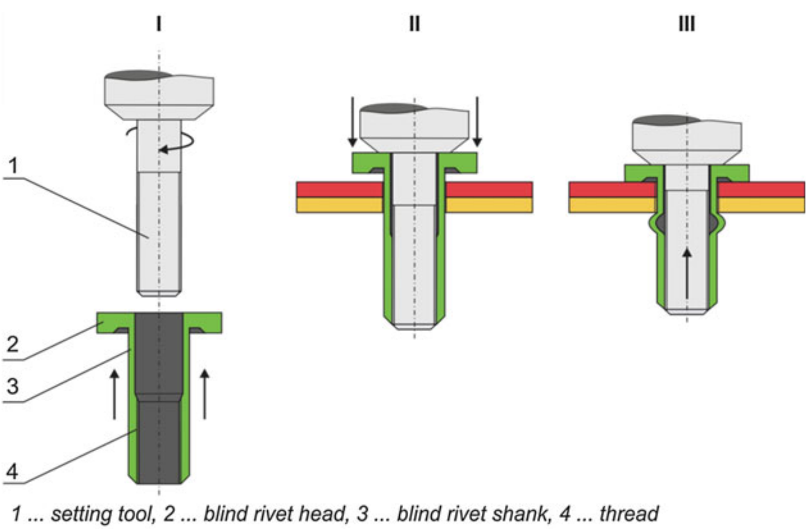



**Mechanical Joining, Fig. 11** Setting process of self-piercing nut




**Mechanical Joining, Fig. 12** Setting process of rivet nut

**Mechanical Joining, Fig. 13** Setting process of blind rivet nut



Research on connection properties of different kinds of the described elements can be found among others in Hahn et al. 1999.

## Cross-References

- ▶ Assembly
- ▶ Bending (sheets)
- ▶ Bonding
- ▶ Hydroforming (Sheets and Tubes)
- ▶ Joining by Upset Bulging
- ▶ Welding

## References


Böllinghaus T, Byrne G, Cherpakov BI, Chlebus E, Cross CE, Denkena B, Dilthey U, Hatsuzawa T, Herfurth K, Herold H, Kaldos A, Kannengiesser T, Karpenko M, Karpuschewski B, Marya M, Marya SK, Matthes KJ, Middeldorf K, Oliveira JFG, Pieschel J, Priem DM, Riedel F, Schleser M, Tekkaya AE, Todtermuschke M, Vereschaka A, von Hofe D, Wagner N, Wodara J, Woeste K (2009) Manufacturing engineering. In: Grote K-H, Antonsson K (eds) Springer handbook of mechanical engineering. Springer, Berlin/Heidelberg, pp 523–785

Budde L, Pilgrim R (1995) Stanznieten und Durchsetzfügen, Systematik und Verfahrensbeschreibung umformtechnischer Fügetechnologien [Self-piercing riveting and clinching, systematology an process descriptions of joining by forming]. Verlag Moderne Industrie, Landsberg/Lech. (in German)

DIN 8593–5 (2003) Fertigungsverfahren Fügen – Teil 5: Fügen durch Umformen; Einordnung, Unterteilung, Begriffe [Manufacturing Technology Joining – Section 5: Joining by forming; Classification, Subdivision, Terms and Definitions]. Deutsches Institut für Normung (DIN) e. V. Beuth, Berlin (in German)

DVS (2009) Taschenbuch DVS-Merkblätter und -Richtlinien. Mechanisches Fügen [Paperback DVS-Instruction Sheets. Mechanical Joining]. Verlag für Schweißen und verwandte Verfahren, Düsseldorf (in German)

Hahn O, Klemens U (1996) Fügen durch Umformen; Nieten und Durchsetzfügen – Innovative Verbindungsverfahren für die Praxis [Joining by forming; Riveting and Clinching – Innovative Joining Technologies for Practice], vol Bd. 707. Düsseldorf, Verlag und Vertriebsgesellschaft Stahlanwendung

Hahn O, Timmermann R (2000) Ermittlung ertragbarer Beanspruchungen von Blindnietverbindungen als Grundlage zur rechnergestützten Auslegung [Determination bearable stresses of blind rivet joints as the basis for computer-aided design]. Ergebnisse eines Vorhabens der industriellen Gemeinschaftsforschung (IGF), Nr. 149. EFB e. V., Hannover (in German)

Hahn O, Jendrny J, Voekner W, Timm M (1999) Kennwertermittlung an selbststanzenden Funktionselementen sowie Niet–/ Einpressmuttern und –bolzen [Determination of characteristic values of self-piercing riveting functional elements and clinch nuts and studs]. Ergebnisse eines Vorhabens der industriellen Gemeinschaftsforschung (IGF), Nr. 143. EFB e. V., Hannover (in German)

Mori K, Bay N, Fratini L, Micari F, Tekkaya AE (2013) Joining by plastic deformation. J CIRP 62(2):673–694. https://doi.org/10.1016/j.cirp.2013.05.004

Neugebauer R, Menzel S, Meyer B, Neumann I (2010) Falzklebeprozess im automobilen Rohbau [Hem flange bonding at the automobile body manufacture]. Ergebnisse eines Vorhabens der industriellen Gemeinschaftsforschung (IGF), Nr. 320. EFB e. V., Hannover (in German)

Psyk V, Risch D, Kinsey BL, Tekkaya AE, Kleiner M (2011) Electromagnetic forming – a review. J Mat Pro Tec 211:787–829. https://doi.org/10.1016/j.jmatprotec.2010.12.012

Riedel F (2004) Möglichkeit der Optimierung von punktförmigen, kraft- und formschlüssigen Feinblechverbindungen am Beispiel Clinchverbindungen und Clinchkonstruktionen [Possibility of optimization of positive and non-positive sheet metal connections using the example of clinched connections and clinched constructions]. Ph.D. Thesis, University of Chemnitz, Chemnitz (in German)

Voelkner W, Liebrecht F, Hahn O, Lappe W (1993) Grundlegende Untersuchung zur Eignung des Stanznietens zum Verbinden von Aluminiumwerkstoffen [Basic investigation of suitability of punch riveting for joining aluminum materials]. Ergebnisse eines Vorhabens der industriellen Gemeinschaftsforschung (IGF), Nr. 50, EFB e. V., Hannover (in German)


# Mechanical Joining

▶ Joining by Upset Bulging

# Mechanical Machining

▶ Cutting, Fundamentals

# Mechanical Micromachining

▶ Micromachining

## Mechanical Surface Modification

► Peening

## Mechanical Surface Treatment

► Peening

## Mechanism

Gabor Stepan
Department of Applied Mechanics, Budapest University of Technology and Economics, Budapest, Hungary

### Synonyms

Kinematic chain; Linkage model; Machine

### Definition

#### Kinematic Chain

An assemblage of links (considered as rigid bodies) and joints, interconnected in a way to provide a controlled output motion of one or more links in response to input motions supplied by actuators.

#### Mechanism

A kinematic chain in which at least one link is "grounded," or attached, to the frame of reference.

### Theory and Application

The major goal of designing a mechanism is to have a working part (body) of the mechanism that undergoes a desired motion (Norton 2004). In the easiest case, the desired motion is only several fixed points and/or orientations in the (3D or 2D) space that the working part needs to pass through. In a complicated case, the complete shape of the path of the working part is given. Moreover, the velocity or acceleration characteristics can be prescribed along the path, too. If the mechanism cannot provide the exact desired motion, then the goal is to provide a motion that is close to the desired motion.

Most of the engineering examples can be realized by 4-bar or 6-bar kinematic chains. It is important to predesign the mechanism geometrically: the types of the linkage connections and the topology of the linkage.

#### Geometry

*Links* are considered rigid bodies (RB) in the mechanical model of the mechanisms.

Degree of freedom (DOF) of a link (RB) is defined as the number of independent scalar functions that uniquely determine the position and orientation of the link in the space.

*Joint* is a connection between two or more links (at their nodes), which allows some motion between the connected links. Joints are also called as *kinematic pairs*. Different types of joints are shown in Table 1

*Mobility of mechanism* (*or DOF of the mechanism*) is the number of inputs, which are needed to provide the prescribed motion. The *general coordinates* $\mathbf{q}(t)$ are the independent scalar functions that uniquely describe the motion of the mechanism. The number of the general coordinates is equal to the mobility of the mechanism. In practice, the mobility gives the necessary number of actuators that are needed to build in the mechanism. In planar case, the mobility of a mechanism can be calculated as (not considering special geometries and paradoxes)

$$M = 3(L - 1) - 2(J_1 - J_2). \qquad (1)$$

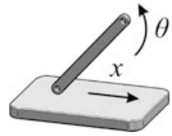
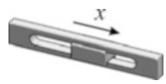
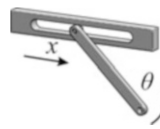
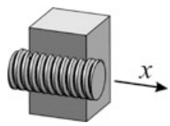
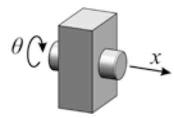
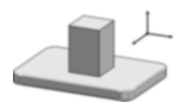
where

$L$ is the number of links in the mechanism,
$J_1$ is the number of full joints in the mechanism, and
$J_2$ is the number of half joints in the mechanism.

Linkages can be classified into open mechanisms and closed mechanisms. *Open mechanisms* have link that has at least one open node (neither

M

**Mechanism, Table 1** Different types of ideal joints that can appear in a kinematic chain

| | 1DOF (full joints) | 2DOF (half joints) | 1- or 2DOF |
|---|---|---|---|
| 2D | Pin joint   | Link against a plane   | May roll, may slide  |
| | Slider   | Pin slider   | 3DOF/3D<br>Spherical joint  |
| 3D | Helical joint   | Cylinder   | Planar joint  |

grounded nor linked). *Closed mechanisms* have no nodes that are not linked or grounded.

## Kinematics

All the parts of the mechanisms are considered as rigid bodies, that is, the deformations of the links during the motion are neglected. Knowing the position, the velocity, and the acceleration inputs (at the actuators), the position, velocity, and acceleration state of any part of the mechanisms can be determined.

### Position Analysis

Position analysis is the determination of the position and the orientation of each link as function of the general coordinates. The position analysis of open mechanisms is direct and explicit, while the position analysis of closed mechanisms usually leads to a system of nonlinear equations that can be generally solved numerically. After the position analysis, the position vectors $\mathbf{r}$ between any nodes of any links can be given with respect to the general coordinates $\mathbf{q}(t)$ analytically or numerically, i.e.,

$$\mathbf{r}_{XY}(t) = \mathbf{r}_{XY}(\mathbf{q}(t)), \tag{2}$$

where $X$ and $Y$ are two subsequent nodes on a selected link of the mechanism. The position w.r.t. the frame of reference can be expressed as

$$\mathbf{r}_Y(t) = \mathbf{r}_X(t) + \mathbf{r}_{XY}(t), \tag{3}$$

### Velocity Analysis

The velocity of a given point $Y$ of a link can be derived as

$$\mathbf{v}_Y(t) = \dot{\mathbf{r}}_Y(t), \tag{4}$$

where dot denotes derivation w.r.t. time. Since the links are rigid bodies, the *velocity state* of a link at time instant $t$ is said to be known if the velocity vector at a point $Y$ and the angular velocity vector $\boldsymbol{\omega}$ of the link are known. The velocity state can be given by the following *pair*

$$[\omega, \mathbf{v}_Y]_Y. \tag{5}$$

of vectors. The velocity of another point of the link can be calculated from $\mathbf{v}_Y$ by means of the reduction formula as

$$\mathbf{v}_X = \mathbf{v}_Y + \mathbf{v}_{XY} = \mathbf{v}_Y + \boldsymbol{\omega} \times \mathbf{r}_{YX}. \tag{6}$$

### Acceleration Analysis

The acceleration of a given point $Y$ of a link can be derived as

$$\mathbf{a}_Y(t) = \dot{\mathbf{v}}_Y(t) = \ddot{\mathbf{r}}_Y(t), \tag{7}$$

The acceleration vector can be separated to tangential and normal components along the local path at $Y$

$$\mathbf{a}_Y = \mathbf{a}_{Y,t} + \mathbf{a}_{Y,n}, \tag{8}$$

The acceleration state of a link in a mechanism is given if the acceleration vector $\mathbf{a}_Y$ at point $Y$ and the angular acceleration vector $\boldsymbol{\varepsilon}$ are known assuming that the velocity state of the link is already determined.

The acceleration of another point of the link can be calculated from $\mathbf{a}_Y$ by means of the reduction formula as

$$\begin{aligned}\mathbf{a}_X &= \mathbf{a}_Y + \mathbf{a}_{XY,t} + \mathbf{a}_{XY,n} \\ &= \mathbf{a}_Y + \boldsymbol{\varepsilon} \times \mathbf{r}_{YX} + \boldsymbol{\omega} \times (\boldsymbol{\omega} \times \mathbf{r}_{\mathbf{YX}}).\end{aligned} \tag{9}$$

## Dynamics

Dynamic analysis gives the equation of motions of the entire mechanism (Ginsberg 1995). Once the accelerations and the internal forces in the structure are known, then the dimensions of the links can be designed.

### Classical Formalism

**Newton-Euler Equations (Newton's Second Law)** The equation of motion is derived using free-body diagrams (FBDs) for each rigid body. The FBDs contain kinematical (acceleration, angular acceleration, angular velocity) and dynamical (external/reaction forces, moments) variables. The Newton-Euler equations consist of two parts, the translational part and the rotational part.

The translational part (for the $i$th body) is

$$\dot{\mathbf{I}}_i = \sum_j \mathbf{F}_{i,j}. \tag{10}$$

where

$\mathbf{I}_i = m_i \mathbf{v}_{i,C}$ is the linear momentum of the $i$th RB with C being the center of gravity and

$\mathbf{F}_{i,j}$ is an external or internal (reaction) force acting on the $i$th RB.

The rotational part (for the $i$th body) is

$$\mathbf{D}_{i,X} = \sum_j \mathbf{r}_{i,Xj} \times \mathbf{F}_{i,j} + \sum_k \mathbf{M}_{i,k}, \tag{11}$$

where

$$\mathbf{D}_{i,X} = \dot{\mathbf{L}}_{i,}X + \mathbf{v}_{i,X} \times \mathbf{I}_{i,X} \tag{12}$$

is the kinetic momentum of the $i$th RB w.r.t. the general point $X$. If $X$ is a permanently steady point or $X$ is the center of gravity, the following simplification holds:

$$\mathbf{D}_{i,X} = \dot{\mathbf{L}}_{i,}X = \Theta_{i,X}\boldsymbol{\varepsilon}_i + \omega_i \times \mathbf{L}_{i,X} \tag{13}$$

$\mathbf{L}_{i,X} = \mathbf{L}_{i,C} + \mathbf{r}_{i,XC} \times \mathbf{I}_i$ is the angular momentum of the $i$th RB w.r.t. point $X$.

$\mathbf{L}_{i,C} = \boldsymbol{\Theta}_{i,C\boldsymbol{\omega}i}$ is the angular momentum w.r.t. the center of gravity C.

$\boldsymbol{\Theta}_{i,C}$ is the mass moment of inertia matrix w.r.t. the center of gravity C.

$\mathbf{r}_{i,XC}$ is the spatial vector that points to the point of application of $\mathbf{F}_{i,j}$.

$\mathbf{M}_{i,k}$ is the reaction moment or external torque acting on the $i$th RB.

$\boldsymbol{\omega}_i$ is the angular velocity of the $i$th link.

$\boldsymbol{\varepsilon}_i$ is the angular acceleration of the $i$th link.

### Virtual Power-Based Formulization

**Lagrange Equation of the Second Kind** This equation provides the equations of motion of a holonomic (having only geometrical constraints) mechanical system (mechanism) in a $k$th-dimensional ODE form. Note that the inner forces are excluded from the equations. The following formula is the so-called *Routh-Voss* equation that is the *Lagrange equation of the second kind* extended to kinematical constraints, too:

$$\frac{d}{dt}\frac{\partial L}{\partial \dot{\mathbf{q}}} - \frac{\partial L}{\partial \mathbf{q}} + \frac{\partial D}{\partial \dot{\mathbf{q}}} = \mathbf{Q} + \mathbf{A}^{\mathrm{T}}\boldsymbol{\mu} \qquad (14)$$

where

$L = T - U$ is the *Lagrange function* that contains the kinetic energy $T$ and the potential function $U$,
$\mathbf{q}(t)$ contains the general coordinates,
$D$ is the dissipative potential that can introduce viscous dampers in the equations of motions,
$\mathbf{Q}$ contains the general forces, and
$\boldsymbol{\mu}$ contains the *Lagrange multipliers*

$$\mathbf{A}(\mathbf{q},t)\dot{\mathbf{q}} + \mathbf{b}(\mathbf{q},t) = 0 \qquad (15)$$

describes the kinematical constraints.

**Lagrange Equation of the First Kind** With this equation, both geometrical and kinematical constrains can be considered, and it usually leads to a mixed differential and algebraic equation (DAE) as the governing equation of motions. The links (RB) of the mechanism can be considered as a specially distributed, equivalent, system of material particles (of mass $m_i$) that describes the mass inertia of the original system, too, with the so-called natural coordinates ($\mathbf{r}_i$). In this way, the definitions of angular velocities and angular accelerations are excluded because of the difficulties in the definition of the angular coordinates. Then, the Lagrange equation of the first kind has the form

$$\begin{aligned} m_i\ddot{\mathbf{r}}_i &= \mathbf{F}_i + \boldsymbol{\Phi}_{\mathbf{r}_i}^{\mathrm{T}}\boldsymbol{\lambda} + \mathbf{A}^{\mathrm{T}}\boldsymbol{\mu}, \\ \boldsymbol{\varphi}(\mathbf{r}_i,t) &= \mathbf{0}, \\ \mathbf{A}(\mathbf{r}_i,t)\dot{\mathbf{r}}_i + \mathbf{b}(\mathbf{r}_i,t) &= \mathbf{0}, \end{aligned} \qquad (16)$$

where

$\mathbf{F}_i$ are the external forces,
$\boldsymbol{\varphi}$ contains the geometric constraints defined in the mechanism, and

$$\boldsymbol{\Phi}_{\mathbf{r}_i} = \frac{\partial \boldsymbol{\varphi}}{\partial \mathbf{r}_i} \qquad (17)$$

$\boldsymbol{\lambda}$ and $\boldsymbol{\mu}$ are the *Lagrange multipliers*.

**Multibody Formulations** Both above-mentioned formulizations can be described by the following common form that is usually used nowadays to describe the so-called multibody systems:

$$\left.\begin{aligned} \mathbf{M}\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q},\dot{\mathbf{q}}) + \boldsymbol{\Phi}_{\mathbf{q}}^{\mathrm{T}}\boldsymbol{\lambda} + \mathbf{A}^{\mathrm{T}}\boldsymbol{\mu} &= \mathbf{Q} \\ \boldsymbol{\phi}(\mathbf{q},t) &= 0 \\ \mathbf{A}(\mathbf{q},t)\,\dot{\mathbf{q}} + \mathbf{b}(\mathbf{q},t) &= 0 \end{aligned}\right\}, \qquad (18)$$

where

$\mathbf{M}$ is the mass matrix,
$\mathbf{q}$ is the vector of the chosen coordinates (can be redundant),
$\mathbf{Q}$ is the load vector, and
$\mathbf{C}$ is a nonlinear function that contains the system damping and stiffness.

In order to avoid the difficult DAE form, one can use the time derivatives of the constraint equations, and stabilization techniques (e.g., Baumgarte stabilization) can be applied in order to avoid possible numerical problems.

## Applications

Several machining centers with open and closed loop mechanisms are listed in the review paper of Weck and Staimer (2002).

## Cross-References

► Dynamics
► Machine Tool

## References

Ginsberg JH (1995) Advanced engineering dynamics. Cambridge University Press, New York
Norton RL (2004) Design of machinery, an introduction to the synthesis and analysis of mechanisms and machines, 3rd edn. McGraw-Hill, New York
Weck M, Staimer D (2002) Parallel kinematic machine tools-current state and future potentials. CIRP Ann Manuf Technol 51(2):671–683

## Mechatronics

Michael F. Zaeh[1] and Robert X. Gao[2]
[1]iwb – Institut fuer Werkzeugmaschinen und Betriebswissenschaften, Technical University of Muenchen, Munich, Germany
[2]Case Western Reserve University, Cleveland, OH, USA

## Definition

Mechatronics is a multidisciplinary engineering science aiming at the synergistic integration of mechanics, electronics, and control theory within product design and manufacturing.

### Extended Definition

The term "mechatronics" is a neologism composed of the words mechanics and electronics and was coined by Yaskawa Electric Corp. in 1969 (Habib 2007). In its original meaning, mechatronics was understood as the functional enhancement of mechanical systems by electronic components (Neugebauer et al. 2007). Benefiting from the rapid advancement in computational power and information technology over the past four decades (Neugebauer et al. 2007; Luo and Chang 2010), the scope of coverage by the term "mechatronics" has exceeded its original meaning of "electromechanics" by incorporating more of the "intelligence" aspects.

Numerous definitions of "mechatronics" can be found in literature (VDI 2004). The quintessence of most definitions is the synergetic cooperation of different engineering disciplines, although there are differences in detail. Therefore, the definition of the Industrial Research and Development Advisory Committee (IRDAC) of the European Commission is exemplarily given in this entry: Mechatronics is the synergetic combination of precision engineering, electronic control technology, and systems thinking in the design of products and processes.

The three core components of a mechatronic system are:

- The mechanical structure
- The electrical components (sensors and actuators)
- The control/communication systems

Modern mechatronic devices may however include further subsystems, e.g., optical or fluidic modules. The terms "optomechatronics" (Cho 2006) and "fluid mechatronics" have been created in this context. Increasing demands for lightweight design and low space requirements call for a higher degree of functional integration in mechatronic systems. Multifunctional, "smart" materials (e.g., piezoceramics) have therefore been developed. These materials offer actuatory and sensory properties and can be directly integrated into the force flow. The term "adaptronics" was created for such systems in order to emphasize the functional integration by use of smart materials (Janocha 2007). Hence, adaptronics can be regarded as a branch of mechatronics.

Furthermore, the expression "mechatronic approach" is common in product development. The traditional sequential design procedure (mechanics → electronics → control/communication), which results in partly optimized products and time- and cost-intensive iterations, is overcome and replaced by an interdisciplinary cooperation of the development teams in the sense of "concurrent engineering" (van Brussel 1996). Thus, optimal products can be developed at reduced costs.

### Evolution of Mechatronics

Since 1969, mechatronics has gone through a progressive evolution, as shown in Fig. 1. In the 1970s, mechatronics primarily focused on servo technology that drives the mechanisms of simple electronically controlled products, such as vending machines and autofocus cameras. At this stage, technology was developed through individual and independent design teams consisting of engineers with different backgrounds and staff in design, manufacturing, purchasing, and marketing (Habib 2007).

Coming to the 1980s and with advancements in digital electronics, mechatronics had evolved into a design methodology and philosophy, which

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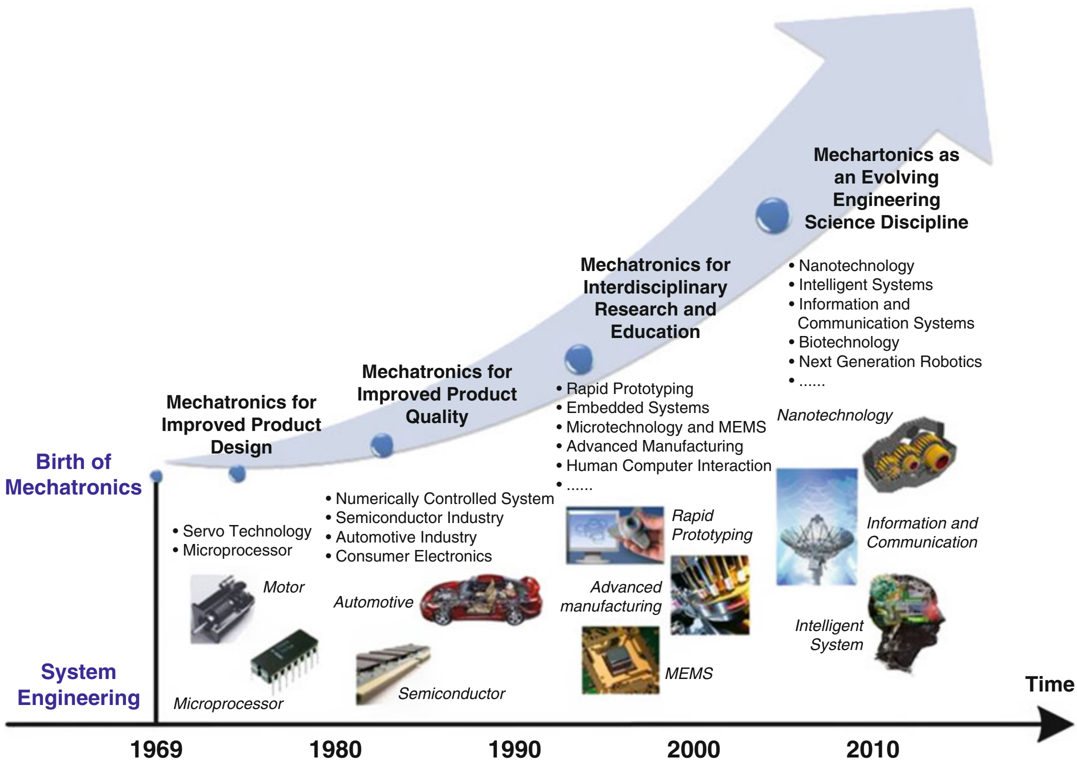



**Mechatronics, Fig. 1** Evolution of mechatronics

synergized and integrated different technologies. The concurrent codesign concept for hardware and software was also developed. The evolution of mechatronics was initially driven by the automotive industry, and later, manufacturing machinery, numerical controller systems, and consumer electronics have caught up. The evolution had also led to an increasing demand for engineers with a mechatronics background. Eventually, universities started building dedicated programs for education and training in mechatronics.

By the 1990s, mechatronics emerged as an interdisciplinary education and research identity. In this era, the focuses of mechatronics were product miniaturization, human-computer interface and interaction, design cycle time reduction, and integration with modern communication and information technologies. Related topics included advanced manufacturing, rapid prototyping, embedded systems, microelectromechanical systems (MEMS), and automation. After the mid-1990s, mechatronics has gained widespread attention, and its importance has been recognized worldwide.

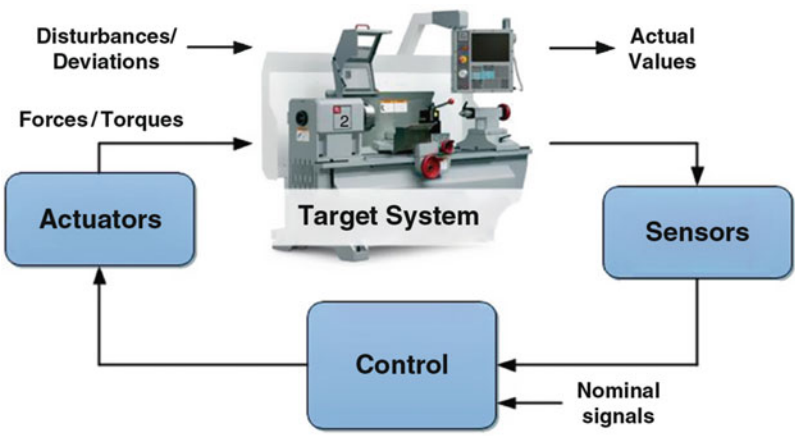
Since 2000, mechatronics has become an engineering science discipline and plays an increasingly important role in solving most of the research issues in modern design and manufacturing, as seen in widely diverse fields such as nanotechnology, biotechnology, intelligent systems, information and communication technologies, and consumer electronics. Mechatronics education has gained immense recognition globally, and a growing number of universities are offering both undergraduate and graduate mechatronics degree courses.

## Theory and Application

### Structure of Mechatronic Systems

Various subsystems interact within a mechatronic device in a complex manner as shown in Fig. 2 (Isermann 2003; de Silva 2005; Necsulescu

**Mechatronics, Fig. 2** Schematic structure of a typical mechatronic device




2009). The individual components of the mechatronic system are therefore often highly integrated with regard to function and space. The block diagram below is also known in control engineering as the basic structure of a closed loop system.

The mechanical components of a mechatronic system accommodate forces and guide movements; they can be interpreted as the "skeleton" of the mechatronic system. Typical mechanical elements are chassis, bearings, guides, and gears. The mechanical structure is connected with the control system via energy transformers, i.e., sensors and actuators. The sensors and transducers detect the relevant system states (position, velocity, pressure, temperature, etc.) by transformation of mechanical, fluidic, or thermal energy into electrical signals that can be processed by the control system. This one calculates the control signals for the actuators so that the actual values track the nominal values. Besides the processing unit, the control system often comprises auxiliary elements like signal amplifiers or filters. The actuators transform the control signals into forces/torques acting on the target system by utilization of electric or fluidic energy, e.g., that is delivered by a power supply.

## Mechatronics in Manufacturing

Machine tools and manufacturing processes are always expected to be precise and productive in order to produce mechanical structures at great precision and at high value of production per employee with reasonable production cost. Precision and productivity together bring scientific and technical challenges in manufacturing design. Especially, the continuous development and advance in microsystem technology and nanotechnology have resulted in a growing demand of precision in machine tools. Mechatronics has then become the key discipline in production technology and advances the development of manufacturing systems (Altintas 2000; Gao et al. 2008, 2010; Altintas et al. 2011) that meet the demands of productive precision.

The individual components in machine tools have various limitations on their corresponding functionality due to either the inherent structures or high-performance requirements. Both general and specific solutions for the relevant limitations and problems faced in typical cutting and forming machines are therefore listed in Table 1.

## Design of Mechatronic Systems

Mechatronic systems excel by various advantages in comparison to classical, electromechanical products (VDI 2004), like

- Improved performance
- Enhanced functionalities
- Smaller installation space
- Reduced cost

However, these advantages can only be achieved by a high degree of functional and spatial integration. But within a conventional,

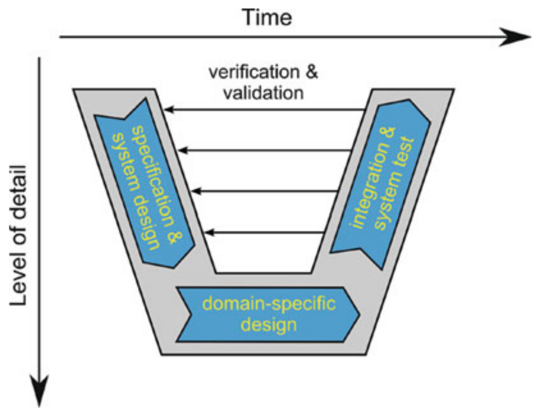
**Mechatronics, Table 1** Mechatronic solutions for machine tools

| Machine tools | Components | Functionality characteristics (limitations) | Mechatronics solutions |
|---|---|---|---|
| Cutting machines | Feed drives | Limited positioning accuracy due to friction | Integration of redundant measuring systems |
| | | Limited control bandwidth | Adaptive electrorheological film damper |
| | | Stiffness and damping of the mechanical structure | Integration of piezo actuators for vibration compensation |
| | | Vibration during highly dynamic use of direct drives | Spindle bearing equipped with sensor-actuator unit |
| | | Increasing thermal loads at high speeds | |
| | Guide systems | Lack of guideway damping | Active hydrostatic guide systems |
| | | Limited positioning accuracy and axis speeds due to Coulomb friction | Active magnetic guide systems |
| | | Dynamic instabilities in passive system | Active aerostatic guide systems |
| | Frame components | Thermal deformations of frame components | Active compensation of thermal deformations through integration of additional actuators |
| | | Restriction of achievable feed bandwidth and performance capability of machines | Active vibration suppression by semi-active and active ancillary systems (e.g., adaptive mass damper, adaptive friction damper) |
| | | High stiffness and damping with low mass required | |
| | | Add-on systems for increasing damping being tuned to fixed frequency ranges | |
| | Main drives | High demands on the static, dynamic and thermal stiffness, and on the life of bearings and spindles | Autonomous adjustment of pre-loading by integrated actuators |
| | | Compromise between stiffness and maximum revolution number when using prestressed bearings | Active bearing support |
| | | Changeable dynamic behavior of main spindle-tool system | Active ancillary bearings |
| | | | Automatic balancing |
| | Tools and clamping devices | Achievable processing precision and metal cutting capacity limited by the low static bending strength and torsional stiffness | Integration of additional actuators |
| | | | Semi-active tunable-stiffness boring bar |
| | | Process stability and achievable metal cutting volume limited by the low stiffness of the tool | Active damping with feedback control |
| | | | Vibration-assisted machining |
| | Grinding wheels | Inhibition of widespread utilization of ceramics for structural components due to high machining cost | Monitoring grinding processes with acoustic emission signals |
| | | Cost-effective machining of ceramics by monitoring the grinding process | Sensor-integrated “intelligent” grinding wheel |
| Forming machines | Main drives | Path-bound presses not responding to the changing process requirements | Superposition of a controllable second drive on the main movement |
| | Frame components | Compensation required for the deflection of the drive and table | Dynamic crowning, pre-deflection of lower beam |
| | Dies | Optimum infeed of sheet metal material | Intelligent multipoint drawing |
| | | Viability of forming processes for high-strength and ultrahigh-strength materials | Tool-integrated solutions |
| | | | Integrated parallel holding |
| | | | Vibration superposition in the forming processes |

sequential design procedure, the individual subsystems of a mechatronic device are designed separately, thus not accounting for the complex interactions caused by the integration (de Silva 2005). Hence, it is not possible (or at least unlikely) to develop an optimal product in sequential order.

Mechatronic design procedures must therefore utilize the potential of interdisciplinary cooperating development teams in the sense of "concurrent engineering" (van Brussel 1996) in order to obtain a holistically optimized product. A challenge that has to be mastered in this context is the creation of a universal nomenclature in order to facilitate the communication between the technical disciplines involved. Moreover, a uniform concept for the description of the interactions between the different subsystems is required. Function-oriented description languages like UML or SysML fulfill this requirement on an abstract level and can thus be used for the design of the superordinate function structure. Furthermore, the appropriate involvement of optional external development partners is an absolute condition for a successful mechatronic development project.

On a more concrete level, development engineers can employ computer-aided simulation systems in order to model, analyze, and optimize the behavior of a mechatronic system. Especially the dynamic interactions of the system components are in the focus of the simulation (e.g., oscillations in drive trains due to load changes). Basically, signal-flow-oriented simulation systems like MATLAB/Simulink or object-oriented simulation systems like Modelica/Dymola are available for this purpose. A common characteristic of these systems is the behavioral description of the subsystems on the basis of mathematical equations. These mathematical equations or substitute models may also be derived from measurements or from domain-specific simulation systems like finite element (FE) or computational fluid dynamics (CFD) programs. Model-based and simulation-based design procedures for complex systems offer significant savings with respect to time and costs. However, it must be taken into account that modeling will take considerable




**Mechatronics, Fig. 3** V model (According to Neugebauer et al. 2007)

initial efforts. Moreover, the plausibility of the simulation results has to be checked constantly – especially in the context of developing completely new products (VDI 2004).

A frequently used generic design procedure for the development of mechatronic products is the so-called V model (Fig. 3). The left, descending branch represents the system design and specification phase, which is characterized by an increasing level of detail: requirement definition → rough system design → detailed system design → domain-specific design → implementation of domain-specific subsystems. The right, ascending branch represents the system integration and test phase, which, in contrast, is characterized by a decreasing level of detail. The different subsystems are integrated in order to create a product matching the requirements. Every step of integration is concluded with a test procedure in order to discover deviations from the required behavior as soon as possible. Generally, a complex mechatronic product cannot be developed within one V model cycle; several cycles are therefore passed from the laboratory specimen over the first prototype to the serial product (Neugebauer et al. 2007).

Moreover, the high degree of integration of mechanical and electr(on)ic components also poses a challenge to the assembly and quality assurance of mechatronic products. Due to that, the "mechatronic approach" is not limited to the product development process only but also comprises the production development process.

## Cross-References

► Actuator
► Sensor (Machines)

## References

Altintas Y (2000) Manufacturing automation: metal cutting mechanics, machine tool vibrations, and CNC design. Cambridge University Press, Cambridge, UK
Altintas Y, Verl A, Brecher C, Uriarte L, Pritschow G (2011) Machine tool feed drives. CIRP Ann-Manuf Technol 60:779–796
Cho H (2006) Optomechatronics: fusion of optical and mechatronic engineering. CRC Taylor & Francis, Boca Raton
De Silva CW (2005) Mechatronics: an integrated approach. CRC Press, Boca Raton
Gao R, Fan Z, Kazmer D (2008) Injection molding process monitoring using a self-energized dual-parameter sensor. CIRP Ann-Manuf Technol 57:389–393
Gao R, Sah S, Mahayotsanun N (2010) On-line measurement of contact pressure distribution at tool-workpiece interfaces in manufacturing operations. CIRP Ann-Manuf Technol 59:399–402
Habib M (2007) Mechatronics: a unifying interdisciplinary and intelligent engineering science paradigm. IEEE Ind Electron Mag 1:12–24
Isermann R (2003) Mechatronic systems: fundamentals. Springer, London
Janocha H (2007) Adaptronics and smart structures: basics, materials, design, and applications. Springer, Berlin
Luo R, Chang C (2010) Multisensor fusion and integration aspects of mechatronics. IEEE Ind Electron Mag 4:20–27
Necsulescu DS (2009) Advanced mechatronics: monitoring and control of spatially distributed systems. World Scientific, Singapore
Neugebauer R, Denkena B, Wegener K (2007) Mechatronic systems for machine tools. CIRP Ann-Manuf Technol 56(2):657–686
van Brussel HMJ (1996) Mechatronics: a powerful concurrent engineering framework. IEEE/ASME Trans Mechatronics 1(2):127–136
VDI 2206 (2004) Design methodology for mechatronic systems. Verein Deutscher Ingenieure (VDI) Guideline, Beuth/Berlin

# Metaheuristic Twist Drill Optimization

► Twist Drill Geometry Optimization

# Metal Cutting Temperature

► Cutting Temperature

# Metal Forming Die

► Forming Tools (Die, Punch, Blank Holder)

# Metal Forming Tool

► Forming Tools (Die, Punch, Blank Holder)

# Metal Spinning

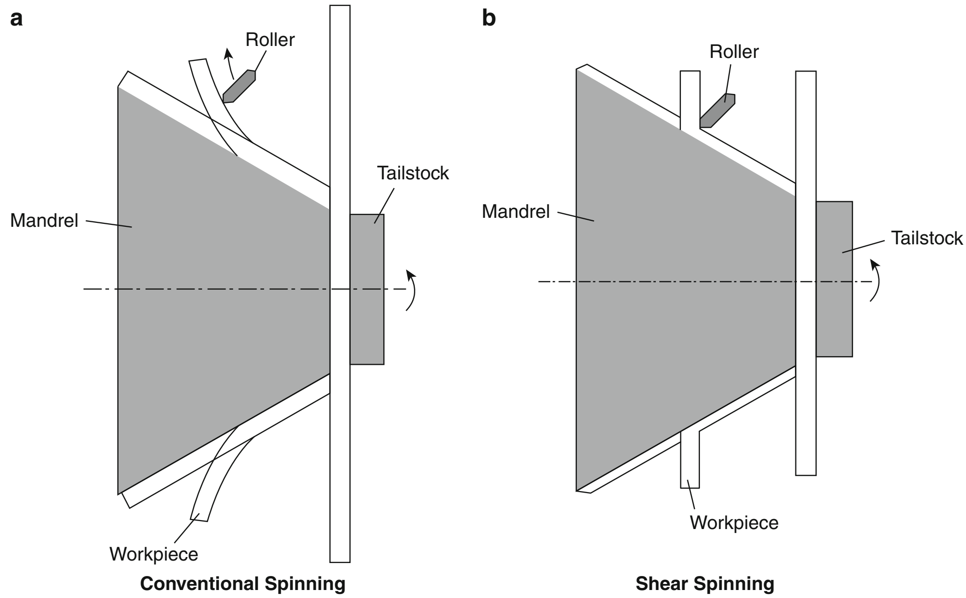
Julian Allwood[1] and James A. Polyblank[2]
[1]Department of Engineering, University of Cambridge, Cambridge, UK
[2]Department of Engineering, Cambridge University, Cambridge, UK

## Definition

The term “metal spinning” describes several distinct processes used to form circular sheets of metal into axisymmetric shells. A circular sheet metal blank is centered relative to a shaped mandrel and held between the mandrel and a tailstock. The sheet, mandrel, and tailstock are then rotated about their shared axis on a spinning lathe, while a working tool (generally a roller) gradually works the sheet toward the mandrel, until it conforms.

## Theory and Applications

Spinning is used to produce axisymmetric shell parts with diameters up to 10 m and with workpieces up to 25 mm in thickness. Almost all parts made by spinning could be made by other




**Metal Spinning, Fig. 1** Shear and conventional spinning

processes, including deep drawing, but the advantages of spinning are:

- Only simple tooling is required – the mandrel can be cut from wood or metal on a lathe, so it is cheap.
- The very local deformation caused by the working tool means that forming forces are low, and so large and expensive presses are not needed, as would be the case in deep drawing or stamping, for example.
- The process can achieve high forming limits, if well controlled.
- The process is very nearly a true net-shape process – with little trimming required after process completion.

Against this, spinning is a relatively slow process (at least compared with stamping or deep drawing), so it is generally used for low-volume production only. In addition, the mechanics of spinning are not well understood, so the process is usually controlled by skilled craft workers who have an intuitive knowledge of the mechanics.

Understanding the mechanics of spinning has been the focus of a great deal of research, which was recently reviewed by Music et al. (2010). They highlighted the difference in mechanics between two distinct forms of spinning in common use: "conventional spinning" (Fig. 1a), in which the outer diameter of the blank reduces during processing and the workpiece is not thinned (although zero thinning is very difficult to achieve in practice) and "shear spinning" (Fig. 1b) in which the outer diameter of the workpiece is not reduced and so the sheet is thinned. The control of the outer diameter and the thickness in shear spinning can be achieved by using a blank holder to prevent diameter reduction or by squeezing the material between the tool and the mandrel in order to achieve the thickness dictated by the sine rule. However, in conventional spinning, constant thickness must be achieved by careful design of the tool path: conventional spinning involved many passes of the tool across the workpiece, where shear spinning often occurs in just one pass.

The mechanics of the two processes are quite distinct. In conventional spinning where the workpiece diameter reduces, deformation involves compressive strain increments in the circumferential direction and tensile strain

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increments in the radial direction. The components of these two increments are generally nearly equal and opposite, leading to a deformation approximately equal to pure shear in the plane of the workpiece, and hence no thinning. In contrast, the strain increments in shear spinning are more nearly in plane strain – with tensile radial increments and little strain in the circumferential direction – so by volume conservation, there is a strong through-thickness thinning effect. The reduction in thickness from $t_0$ to $t_1$ is related to the wall angle, $\alpha$, by the "sine law":

$$t_1 = t_0 \sin \alpha$$

The characteristic failure of shear spinning occurs due to thinning; at some limiting surface angle, the workpiece is too thin to resist any further deformation so fractures. This failure mode may also occur in conventional spinning, but a more common failure when spinning a new part occurs when the workpiece develops plastic wrinkles at its outer circumference. These wrinkles are the result of instability in the thin workpiece – although the ductility of the metal could allow for a large compressive strain, in reality, buckling will occur with even very small compressive circumferential strains. As a result, the art of designing tool paths for conventional spinning is to find paths which avoid excessive thinning or fracture while also avoiding instability from occurring in the outer circumference of the workpiece. Hayama et al. (1970) investigated various tool paths and concluded that an involute shape would allow the greatest spinning ratio (defined as the ratio of the diameter of the blank to the diameter of the product), and Liu et al. (2002) confirmed that involute tool paths resulted in the lowest radial and tangential strains and stresses. However, despite a great deal of research, to date, a complete strategy for tool path generation remains elusive. For some materials, workpieces also crack during spinning, due to excessive work hardening, and this may be alleviated by warm spinning, such as that described by Mori et al. (2009), or by an annealing step during the process.

The greatest contributor to knowledge about spinning has been Professor M. Hayama who worked on the process in Japan from 1963 to 1992. Subsequently several groups in Germany, the largest of which is at the Institute of Forming Technology and Lightweight Construction (ILU) in Dortmund, have continued process exploration of the conventional process, for example, by using force feedback (von Finckenstein and Dierig 1990) or case-based reasoning approach to process design (Ewers 2005). Additionally, novel process designs have been developed in Japan and the United Kingdom and are included in the review by Music et al. (2010).

Spinning has been examined with the full range of numerical methods, but is a difficult problem to examine with finite element methods, because the contact between tool and workpiece changes continuously during production. Hence, a fine mesh with small time increments must be used to model a slow process – leading to very slow solution times. The objective of most numerical modeling research in spinning should be to identify successful strategies for tool path design (although many researchers become distracted by the analysis of tool forces, which provides very little information beyond the necessary size of tooling). However, little progress has yet been made. Most other current researches are to develop extensions of the process, aiming at making non-axisymmetric parts – an idea first investigated by Amano and Tamura (1984) using a radially offset roller to form elliptical parts.

## References

Amano T, Tamura K (1984) The study of an elliptical cone spinning by the trial equipment. In: Proceedings of the 3rd international conference on rotary metalworking processes (ROMP 3). IFS (Publ) Ltd, Kempston, pp 213–224

Ewers R (2005) Prozessauslegung und Optimierung des CNC-gesteuerten Drückens [Process design and optimization in sheet metal spinning], Dissertation, Fachbereich Maschinenbau, Technische Universität Dortmund (in German). Technische Universitat Dortmund, Dortmund

Hayama M, Kudo H, Shinokura T (1970) Study of the pass schedule in conventional simple spinning. Bull Jpn Soc Mech Eng (JSME) 13(65):1358–1365

Liu JH, Yang H, Li YQ (2002) A study of the stress and strain distributions of first-pass conventional spinning

under different roller-traces. J Mater Process Technol 129(1):326–329
Mori K, Ishiguro M, Isomura Y (2009) Hot shear spinning of cast aluminium alloy parts. J Mater Process Technol 209(7):3621–3627
Music O, Allwood JM, Kawai K (2010) A review of the mechanics of metal spinning. J Mater Process Technol 210(1):3–23
von Finckenstein E, Dierig H (1990) CNC-Drücken [CNC-spinning]. CIRP Ann Manuf Technol 39(1):267–270 (in German)

## Metalworking Fluid

▶ Cutting Fluid

## Metalworking Fluids

▶ Grinding Fluids

## Metrology

José A. Yagüe-Fabra
Design and Manufacturing Engineering, Universidad de Zaragoza Instituto de Investigación en Ingeniería de Aragón (I3A), Zaragoza, Spain

### Synonyms

Measurement engineering; Measurement technique; Science of measurement

### Definition

Technological field related to the procedures, equipment, and techniques used in the performance of measurements. Metrology includes all aspects both theoretical and practical with reference to measurements, whatever their Uncertainty and in whatever fields of science or technology they occur. Metrology deals with units and standards, the principles of measurement, the methods and the performance of measurement as well as measuring instruments, the theory of errors, and the determination of physical constants and material properties by measuring.

Note: "Metrology" is more frequently used than its synonyms "measurement engineering" or "measurement technique," particularly where not only the mere technical realization of a measuring task is addressed but also the scientific/methodological background.

### Theory and Application

#### History

Measurement has been an integral part of our everyday lives since antiquity from commercial transactions to building the pyramids (Bosch 1995). First reference standards were regional or local, based on human morphology with units such as the length of an arm or a foot. Therefore, these units of measurement were not fixed and they varied from one town to another, from one occupation to another, and on the type of object to be measured. This lack of a standardization was a source of error and fraud in commercial transactions and a strong limitation for international commerce and development of science. With the expansion of industry and trade, there was an increasing need for harmonization of measures. This harmonization was sought by adopting standards based on Nature (étalon).

The meter was defined based on the size of the Earth in a decree of the French National Assembly on 7 April 1795 as being equal to the ten millionth part of one quarter of the terrestrial meridian. The length of the terrestrial meridian was calculated by measurements undertaken between Dunkerque and Barcelona. A further step for the harmonization of measures was the Convention of the Meter, signed in Paris on 20 May 1875 and amended in 1921. This is a treaty that created the International *Bureau International des Poids et Mesures* (BIPM), Bureau of Weights and Measures, an intergovernmental organization under the authority of the General Conference on Weights and Measures (CGPM), and the supervision of an elected executive body, the International Committee for Weights and Measures (CIPM). The BIPM acts in matters of world metrology, particularly concerning the demand for measurement standards of an ever-increasing accuracy, range, and diversity and the need to demonstrate equivalence between national measurement standards. The Convention of the Meter established a permanent organizational structure for member governments to act in common accord on all matters relating to units of measurement.

This process of standardization further led to the creation of the *Système International d'Unités* (International System of Units, international abbreviation SI) in 1948 through a resolution of the ninth CGPM. Though this is not the official system of units of all nations, the definitions and specifications of SI are globally accepted and recognized (BIPM 2006, 2014). After the introduction of new units by the SI (Table 1), they are then established and maintained through various agencies or national metrology institutes in each country, and establish a hierarchy of measurement standards that can be traced back to the established standard unit, a concept known as metrological Traceability.

The 11th CGPM in 1960 laid down rules for the prefixes, the derived units, and other matters to be used according to the SI. The base units are a choice of seven well-defined units which by convention are regarded as dimensionally independent: the meter, the kilogram, the second, the ampere, the kelvin, the mole, and the candela. Derived units are those formed by combining base units according to the algebraic relations linking the corresponding quantities (JCGM 200 2012).

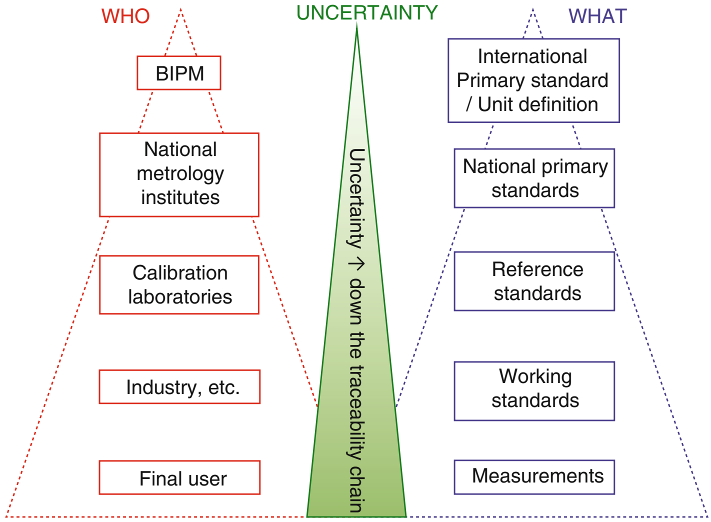
## Categories of Metrology

Metrology is traditionally classified into three categories with different levels of complexity and accuracy (EURAMET 2008):

1. *Scientific or fundamental metrology*: it deals with the organization and development of measurement standards and with their maintenance. It concerns the establishment of quantity systems, unit systems, the development of new measurement methods, development of measurement standards, and the chain of traceability from these reference standards to users in society. This can be considered as the highest level of metrology.
2. *Industrial metrology*: it has to ensure the adequate functioning of measurement instruments used in industry, in production, and in testing processes, for ensuring quality of life for citizens and for academic research. It concerns

**Metrology, Table 1** Base units according to the SI

| Base unit | Symbol | Definition |
|---|---|---|
| Meter | m | It is the length of the path travelled by light in vacuum during a time interval of 1/299,792,458 of a second |
| Kilogram | kg | It is the unit of mass; it is equal to the mass of the international prototype of the kilogram |
| Second | s | It is the duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium 133 atom |
| Ampere | A | It is that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross section and placed 1 m apart in vacuum, would produce between these conductors a force equal to $2 \times 10^{-7}$ N per m of length |
| Kelvin | K | It is the unit of thermodynamic temperature; it is the fraction 1/273.16 of the thermodynamic temperature of the triple point of water |
| Mole | mol | It is the amount of substance of a system which contains as many elementary entities as there are atoms in 0.012 kg of carbon 12. When the mole is used, the elementary entities must be specified and may be atoms, molecules, ions, electrons, other particles, or specified groups of such particles |
| Candela | cd | It is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency $540 \times 10^{12}$ Hz and that has a radiant intensity in that direction of 1/683 W per sr |




**Metrology, Fig. 1** Scheme of the traceability chain


**Metrology, Fig. 2** Picture of a metrology laboratory (University of Zaragoza, Spain)

the application of measurement science to manufacturing and other processes, calibration of the instruments, and quality control of measurements.

3. *Legal metrology*: it is concerned with measurements where these influence the transparency of economic transactions, particularly where there is a requirement for legal verification of the measuring instrument. Some examples of fields where legal metrology applies are health, public safety, enabling taxation, protection of consumers, fair trade, etc.

## Traceability Chain

A measurement standard or reference standard is a material measure, measuring instrument, reference material, or measuring system intended to define, realize, conserve, or reproduce a unit or one or more values of a quantity to serve as a reference.

The relation between a measurement result and reference standards is obtained through a traceability chain. A Traceability chain (see Fig. 1) is an unbroken chain of comparisons, all having stated uncertainties. This ensures that a measurement result or the value of a standard is related to references at the higher levels, ending at the primary standard.

A basic tool in ensuring the traceability of a measurement is the calibration. Calibration determines the performance characteristics of an instrument, system, or reference material. It is usually achieved by means of a direct comparison against measurement standards or certified reference materials. Calibration establishesraceability but it is also necessary to determine the Accuracy of the instrument readouts.

Environmental conditions are an issue when calibrations are carried out (Pfeifer 2002). Therefore, calibrations are performed in metrology laboratories (see Fig. 2).

Uncertainty is a quantitative measure of the quality of a measurement result, enabling the measurement results to be compared with other results, references, specifications, or standards. Measurement uncertainty can be determined in different ways. A widely used and accepted by the accreditation bodies is the ISO-recommended method described in the "Guide to the expression of uncertainty in measurement" (GUM) (JCGM 100 2008).

### Other Related Basic Concepts

When measuring and when expressing the result of a measurement, some concepts of great importance apply. They have to be taken into account in order to give an adequate result of the measurement. Some of these concepts have already been mentioned here. Other key concepts can be found in the following Cross-References section.

## Cross-References

▶ Accuracy
▶ Error
▶ Measurement Uncertainty
▶ Precision
▶ Traceability

## References

Bosch JA (1995) Coordinate measuring machines and systems. Marcel Dekker, New York

Bureau International des Poids et Mesures (BIPM) (2006) The international system of units (SI), 8th edn. http://www.bipm.org/en/si/si_brochure/. Date of Access 17 Jan 2017

Bureau International des Poids et Mesures (BIPM) (2014) The international system of units (SI), Supplement 2014: updates to the 8th edn. (2006) of the SI Brochure. www.bipm.org/utils/common/pdf/si_supplement_2014.pdf. Date of access 17 Jan 2017

European Association of National Metrology Institutes (EURAMET) (2008) Metrology – in short, 3rd edn. http://www.euramet.org/publications-media-centre/documents/metrology-in-short/. Date of access 17 Jan 2017

JCGM 100:2008. GUM 1995 with minor corrections (2008) Evaluation of measurement data – guide to the expression of uncertainty in measurement (GUM) (ISO/IEC Guide 98-3) joint committee for guides in metrology,1st edn. http://www.bipm.org/en/publications/guides/gum.html. Date of access 01 Jan 2017

JCGM 200:2012 (2012) International vocabulary of metrology – Basic and general concepts and associated terms (VIM) 3rd edition (ISO/IEC Guide 99). Joint committee for guides in metrology. http://www.bipm.org/en/publications/guides/vim.html. Date of access 17 Jan 2017

Pfeifer T (2002) Production metrology. Oldenbourg, München

# Micro Deep Hole Drilling

▶ Deep Hole Drilling with Small Diameters

# Micro End Mill

▶ Ultra Small Micro End Mills

# Micro Geometry

▶ Cutting Edge Geometry

## Micro Peening

▶ Peening

## Micro Replication

▶ Microstructure

## Micro Surface Structures

▶ Microstructure

## Micro Tool

▶ Ultra Small Micro End Mills

## Micro-/Nano-finishing

▶ Finishing

## Micro-drilling

▶ Micromachining

## Microgrinding

▶ Ultraprecision Grinding

## Microhoning

▶ Superfinishing

## Micromachining

Paul Mativenga
School of Mechanical, Aerospace and Civil Engineering (MACE), The University of Manchester, Manchester, UK

### Synonyms

Mechanical micromachining; Micro-drilling; Micromachining; Micromanufacturing; Micro-milling; Micro-turning

### Definition

#### Definition of Micromachining

Mechanical micromachining or commonly known as micromachining is a manufacturing technology that involves the use of mechanical micro tools with geometrically defined cutting edges in the subtractive fabrication of devices or features with at least some of their dimensions in the micrometer range (1–999 μm). A micrometer is one millionth of a meter. In the field of machining, very small products are not fabricated easily; therefore, micromachining also indicates products too small to be machined easily.

For micro-milling or micro-drilling processes, when 1–999 μm diameter end mills or drills are used at undeformed chip thickness comparable to the cutting edge radius or material grain size, this presents a challenge for machining and could be considered as a micromachining domain. However, the micro-macro border is sometimes set around 500 μm with some variation among different methods (Masuzawa 2000).

Since there is ambiguity in the definition of mechanical micromachining (micromachining), the following criteria for mechanical micromachining are introduced:

1. The use of a tool with defined cutting edges in machining workpiece dimensions or features between 1 and 500 μm in length scale.

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2. When in machining, the undeformed chip thickness is comparable to the workpiece grain size.
3. When the workpiece grain size(s) and the undeformed chip thickness is in the nanoscale range to a few micrometers in length scale and comparable to the tool edge radius.

Due to the size effect, the mechanics of macromachining can be different from conventional and macroscale machining and can require modification of cutting fundamentals.

## Theory and Application

### Principles and Mechanisms

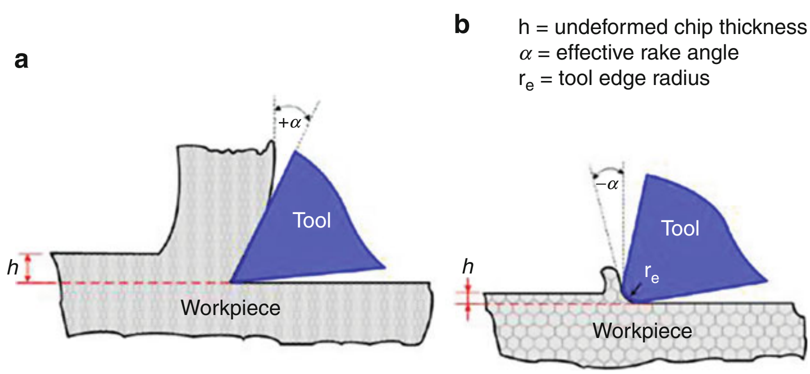
The manufacturing technology has special challenges or process know-how and science stemming from the scaling down of the material removal process and tooling. The main challenge concerning mechanical micromachining is the material removal mechanism whereby well-established laws from the macro-machining domain may not be directly applicable for micromachining. The differences are due to changes in the process mechanics or physical phenomena. This is usually referred to as the size effect. The mechanics of conventional/macroscale cutting in comparison to microscale/nanoscale cutting is illustrated in Fig. 1.

For micromachining, the size effect implies the following:

1. Workpiece material microstructure may not display homogenous property response if the thickness of the material to be removed is smaller or comparable to the grain size of the phase or phases in the workpiece material.
2. If the thickness of the material to be removed is comparable or smaller than the edge radius of the micro tool, then the effective rake angle of the tool becomes highly negative. This presents a challenge on shaping materials by simple shear. Thus, in micromachining, ploughing and shearing of the workpiece material commonly occur simultaneously.
3. In micromachining, there is a significant increase in the specific cutting force when chip thickness is reduced.
4. There is a lower limit for the depth of cut and feed rate that can be set in micromachining, and this is called the minimum chip thickness. This minimum chip thickness is the undeformed chip thickness, below which chip formation does not occur.

## Minimum Chip Thickness

The minimum chip thickness in micromachining is defined as a critical minimum undeformed




**Micromachining, Fig. 1** Schematic representation of effect of cutting edge radius in (**a**) conventional/macroscale machining and (**b**) micro/nanoscale machining thickness of material to be removed (theoretical chip size), below which chips are not formed from the workpiece. The tool/work interaction and the resistance to plastic deformation are factors influencing the value of minimum chip thickness for different work materials. Recent studies suggest that the minimum chip thickness is a small fraction of the tool edge radius (usually 5–43% of the tool edge radius). Acoustic emission signals can be used to evaluate the minimum chip thickness (Mian et al. 2011).

There is compromise to be struck in selecting a sharper cutting tool in order to reduce the minimum chip thickness or selecting a blunter cutting tool in order to reduce tool deterioration and wear rate. Commercially available ultrafine grain carbide micro tools in the year 2016 can have edge radius that is about 1 μm or a couple of micrometers in size. The demands for more accurate micro-cutting (closer to nanoscale cutting) can be met through the use of diamond tools which have a smaller cutting edge radius typically in the order of 50–100 nm. This hence reduces the minimum chip thickness and allows for smaller chip loads to be utilized. The choice of diamond cutting tools or diamond-tipped micro tools is limited by compatibility to workpiece material, type of process, and cost considerations.

## Surface Roughness in Micromachining

At the microscale, the performance of surfaces is even more critical, and hence in most cases, it is important to machine components to achieve a very good surface finish. For example, the surface roughness obtained machining H13 tool steel using solid carbide tools, 500 μm in diameter, is shown in Fig. 2.

Typically in machining, reducing the undeformed chip thickness will result in an improvement in surface finish. This trend can be observed in the right-hand portion of Fig. 2, where the feed per tooth is larger than the tool edge radius, i.e., $f_z > r_e$. However, in micromachining, there is a lower limit to this effect. If the chip load becomes smaller than the effective radius of the cutting edge, i.e., $f_z < r_e$, a different phenomenon can be observed. Rather than the surface finish

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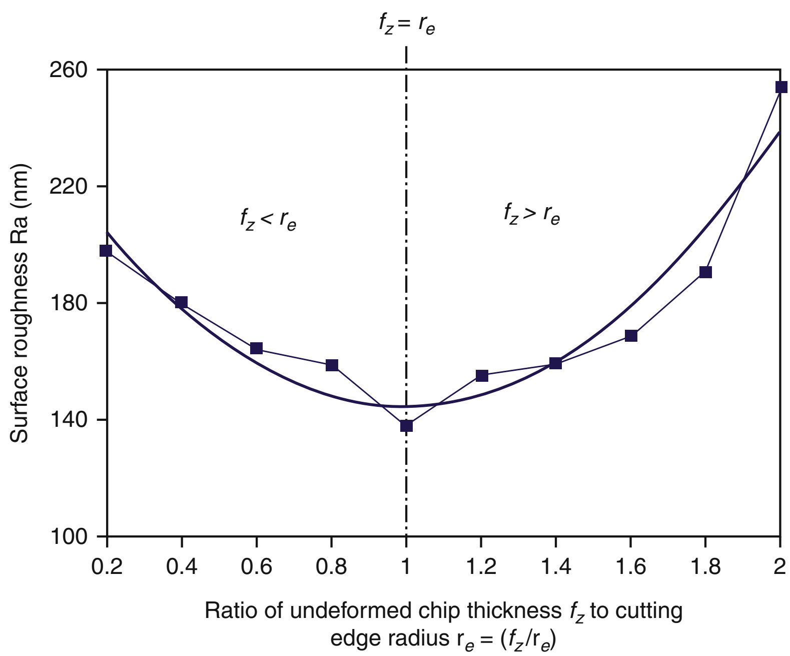
**Micromachining, Fig. 2** Surface roughness in micro-milling of 45HRc H13 tool steel using a 900 μm diameter tool, at 30,000 rpm, 50 μm depth of cut at feed rates of 12–216 mm/min with an initial micro tool edge radius of 1–2 μm. (Adapted from Aramcharoen and Mativenga 2009)



improving with reduced chip loads, surface roughness actually increases. This effect can be seen in the left-hand side of the graph in Fig. 2, where $f_z < r_e$. As chip load reduces to levels below that of the cutting edge radius, the ploughing effect increases. Under these conditions, the cutting edge can be considered blunt and can no longer shear material effectively. This results in elastic deformation and recovery playing a more important role in the mechanics of the process. This trend and phenomenon needs to be evaluated for different workpiece materials and for multiphase materials (Mian et al. 2010) in order to establish a manufacturing process window.

## Burr Formation and Size Control

Burr (sharp extended material over a machined edge) formation is another critical factor in microscale machining since it affects the capability to meet desirable tolerance and geometry definition and assembly of parts. In micromachining, entrance, exit, and top (burrs occurring along the side wall of a slot or tool pass) burrs can occur (Lee and Dornfeld 2002). The factors which influence burr formation are cutting speed, undeformed chip thickness, tool sharpness, tool-feed modes, and workpiece materials. The mechanism of burr formation in micromachining is dominated by the interaction between cutting edge radius and undeformed chip thickness. When the ratio of undeformed chip thickness to the cutting edge radius decreases, this means that the effective rake angle becomes more negative. In this case, material ahead of the tool is pushed/compressed. A portion of the material flows away deforming plastically into a burr.

In micro-milling, down milling mode generates larger wavy-type burrs, while up milling mode produces smaller ragged-type burrs. Cutting edge radius and progression of tool wear are factors driving burr size growth. To reduce burr size, a cutting tool with a very small edge radius should be selected, and the tool can be coated to extend its life. Additionally, the mode of cutting for finishing passes can be controlled.

## Material-Dependent Machining Process Windows

### Micromachining of Multiphase Ductile Materials

For multiphase material, plastic strain mismatch and higher absorption of energy at the harder phase influence surface dimple formation. Manufacturing improvements include (i) where applicable, refining the grain of the workpiece material to improve its microscale machinability, (ii) selecting an appropriate grain orientation for machining – though this is difficult in practice and grain orientation can also be disturbed by previous cuts, (iii) selection of undeformed chip thickness relative to material grain structure, and (iv) optimizing the ratio of undeformed chip thickness to the tool edge radius.

### Micromachining of Brittle Material in Ductile Mode

Ductile-mode micro-cutting is aimed at suppressing fracture in micro- or nanoscale machining of brittle materials like silicon wafers. Ductile-mode cutting can be achieved if the compressive stresses in the chip formation zone are kept at an extremely high level. This level should be high enough so that in the chip formation zone, crack propagations are suppressed. For this to be achieved, the cutting edge radius should typically be in the nanoscale range, and the undeformed chip thickness should be smaller than the tool cutting edge radius. This means that the mode of cutting is ploughing. Diamond turning is typically used for ductile-mode machining of silicon.

## Applications for Micromachining

Micromachining can be a key technology for machining of micro components, micro features, or components that lie between the macroscale and microscale domain (mesoscale components). Some typical applications for micromachining are listed below:

Drilling micro holes for effusion cooling, printed circuit boards, SEM aperture strips, inkjet

nozzles, spray nozzles, satellite apertures, medical devices, and micro molds
Automotive fuel injectors and nozzles
Diamond-milled or turned micro grids, for optics, and also for functional surfaces
Dental implants
Electroless nickel molds for CD/DVD pickup lenses
Machining of biocompatible materials for medical devices
Machining of components for micromachines
Machining of customized micro-sized electrodes from copper or graphite
Machining of micro molds and dies for a variety of applications including plastic parts mass manufacture
Micro-milling of tool-steel microinjection molds
Machining of microsurgical equipment
Machining of optical glass and fibers components
Machining of metal and ceramic matrix composite components
Specialist defense/security applications
Tool and mold making
Wafer machining in ductile mode
Watch and jewellery industry making

## Cross-References

▶ Chip-Forms, Chip Breakability, and Chip Control
▶ Coated Tools
▶ Cutting, Fundamentals
▶ Deep Hole Drilling with Small Diameters
▶ Roughness
▶ Wear Mechanisms

## References

Aramcharoen A, Mativenga PT (2009) Size effect and tool geometry in micro milling of tool. Precis Eng 33(4):402–407. https://doi.org/10.1016/j.precisioneng.2008.11.002
Lee K, Dornfeld DA (2002) An experimental study on burr formation in micro milling aluminium and copper. Trans NAMRI/SME 30:255–262
Masuzawa T (2000) State of the art of micromachining. CIRP Ann Manuf Technol 49(2):473–488
Mian A, Driver N, Mativenga PT (2010) A comparative study of material phase effects on micro-machinability of multiphase materials. Int J Adv Manuf Technol 50(1–4):163–174. https://doi.org/10.1007/s00170-009-2506-9
Mian AJ, Driver N, Mativenga PT (2011) Estimation of minimum chip thickness in micro milling using acoustic emission. Proc IME B J Eng Manuf 225(9):1535–1551

## Micromanufacturing

▶ Microstructure
▶ Micromachining

## Micro-milling

▶ Micromachining

## Micro-scale Features

▶ Microstructure

## Microstructure

Fengzhou Fang[1,2] and Nan Zhang[1,2]
[1]The State Key Laboratory of Precision Measuring Technology and Instruments, Centre of MicroNano Manufacturing Technology, Tianjin University, Tianjin, China
[2]Centre of MicroNano Manufacturing Technology (MNMT-Dublin), University College Dublin, Dublin, Ireland

### Synonyms

Micromanufacturing; Micro-scale features; Micro replication; Micro surface structures

### Definition

Microstructure is defined as surface details at micrometric length scale, which can be also called as “micro-scale features”, or “micro surface structures.” Here “microstructure” is particularly referred as surface details rather than a material’s internal structure.

## Theory and Application

### Introduction

Surface microstructures are basic elements that form a functional surface, such as a Fresnel lens, adhesive structures, cell culture dishes, microfluidic devices, and heat transfer fins. A Fresnel lens has a series of periodic refractive structures of concentric prisms with pitch size in micrometre scale. The surfaces of these prisms are designed to refract light by collapsing the surface curvature of a conventional lens nearly into a plane. A microfluidic chip generally has channel dimensions from tens to several hundred micrometers in order to manipulate a small amount of liquid. A cell culture dish has periodic patterns ranging from several micrometers to hundreds of micrometers to enhance cell proliferation, dependent on cell lines. In all these applications, surface microstructures play an important role, and the design of microstructured product requires understanding of material properties, manufacturing processes, and applications.

### Materials and Applications

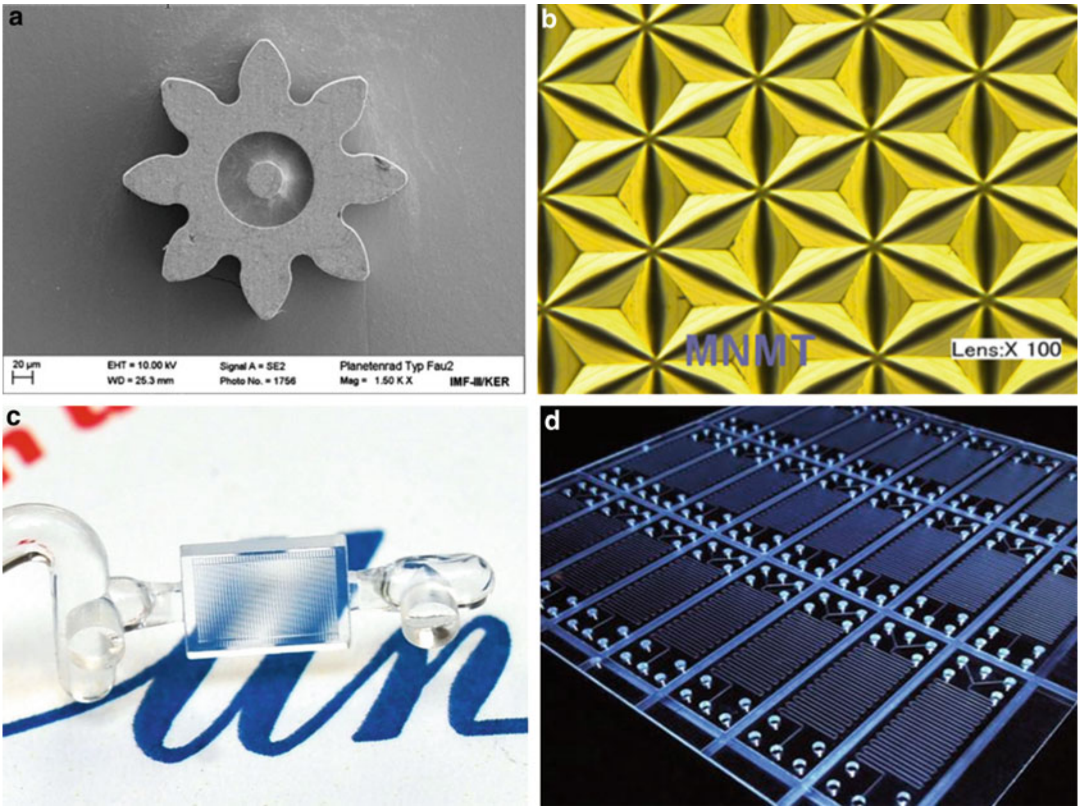
Many materials can be used for the manufacturing of microstructured products, such as ceramics, glasses, semiconductors, metals, and plastics, dependent on a particular application. Ceramic parts with microstructure, such as a micro gear (Fig. 1a), have been used in many fields, such as precision engineering, dental surgery, lock parts, etc. Semiconductor materials, typically silicon, are basic elements for integrated circuits with line widths ranging from micrometer to nanometer. Semiconductor micro-fabrication process has been applied for fabrication of masters with micro-scale protrusions/cavities for microfluidic devices and photonic devices and cell culture plates for various molding process, such as soft lithography, injection molding, and hot embossing. Metallic microstructured surfaces, such as stainless steel, could be employed as ideal molds for plastic injection molding manufactured by various micromanufacturing processes. Metal itself can be used as a product with functional surfaces, such as an optical reflector with micro-scale pyramid structures (Fig. 1b). Plastic materials, including thermoplastics, thermosets, and elastomers, are widely used in medical and optical industry, because of its mass production capability and low cost. They are fundamental materials for microlens arrays (Fig. 1c), microstructured cell culture devices, microfluidic devices (Fig. 1d), and functional optical/bio surfaces. Glass with good inert chemical properties (acid resistance and organic solvent resistance) can be a good material for diagnostic devices, such as microfluidic chip for processing chemicals in harsh environment. The high transparency of glass makes it an excellent material for optical industry, such as compound eyes and optical gratings.

### Manufacturing Processes for Surface Microstructures

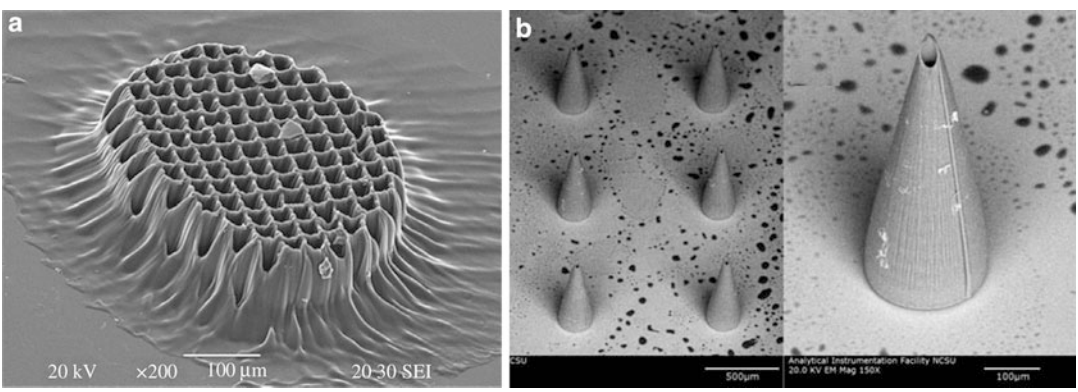
Both conventional and nonconventional methods are used to manufacture microstructured products. Based on the way the surface microstructures are produced, the manufacturing processes can be classified into additive, subtractive, and micro replication processes (Qin 2010).

#### Additive Manufacturing

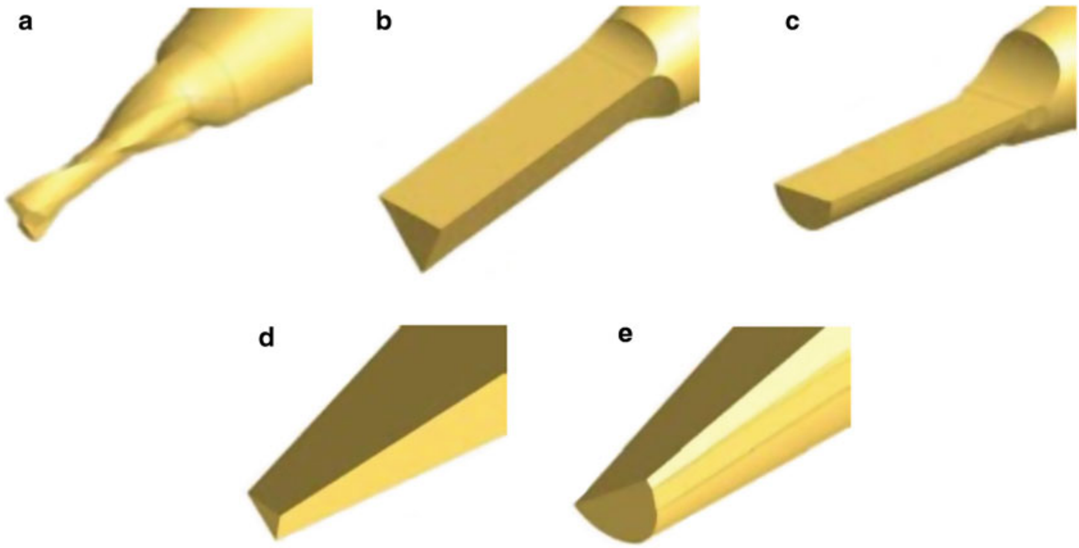
Additive manufacturing includes surface coating using chemical/physical vapor deposition, direct inkjet writing, selective laser sintering/melting, stereolithography, and laminated object manufacturing. Here stereolithography is used as an example for the fabrication of micro-scale surface structures. Stereolithography is a prototyping method for fabrication of micro-scale features in a layer-by-layer fashion based on photopolymerization, a process by which light causes chains of molecules to be linked together to form polymers. Figure 2a shows a biodegradable photopolymer scaffold with square-shaped pore structures (line width of 7 μm and spacing of 27 μm). Figure 2b is a 710 μm tall individual




**Microstructure, Fig. 1** Microstructures made by various materials: (**a**) Gear wheel made of $ZrO_2$ (outer diameter 275 μm) by micro injection molding (Müller et al. 2009) (Courtesy of Springer), (**b**) micro pyramid structures manufactured by single-point diamond turning using copper, (**c**) micro injection molded plastic aspheric micro-lens arrays, (**d**) plastic microfluidic chip machined by micromilling (http://www.micronit.com/technologies/fabrication-technologies/polymer-microfabrication/; Courtesy of Micronit)




**Microstructure, Fig. 2** (**a**) SEM image of biodegradable poly(propylene-fumarate) and diethyl fumarate polymerized grid with a square-shaped pore structures fabricated by UV excimer laser photocuring at wavelength of 308 nm (Beke et al. 2012) [http://creativecommons.org/licenses/by/4.0/]. (**b**) SEM images of 710 μm tall individual hollow microneedle on glass substrates, which were produced using two-photon polymerization based on femtosecond laser (Reproduced from Gittard et al. (2011) with permission from the Royal Society of Chemistry)




**Microstructure, Fig. 3** Various types of end mills in micromachining: (**a**) two-flute end mills, (**b**) **Δ**-type end mills with a straight body, (**c**) D-type end mills with a straight body, (**d**) **Δ**-type end mills with a tapered body, and (**e**) D-type end mills with a tapered body (Fang et al. 2003) 

hollow microneedle on a glass substrate printed by two-photon polymerization.

### Subtractive Manufacturing

Subtractive manufacturing describes a process by which 3D objects are constructed by successively removing material away from a solid block of material.

**Mechanical Machining Process** For the machining of micro surface structures, micromachining techniques are widely used for manufacturing microstructured molds, micro sensors, biomedical devices, and microfluidic devices using metallic, polymeric, and ceramic materials. Such processes include microturning, micromilling, microdrilling, and microgrinding. Microcutting is similar to the conventional cutting operation. Surface of the workpiece is mechanically removed using tools, but the depth of cut is normally at the level of micrometers or less. At this scale, tool cutting-edge geometry, grain size, and orientation become significant factors with strong influences on the resulting machining accuracy, surface integrity, and quality. Micromilling tool failure mode was studied by using various tool geometries, as shown in Fig. 3 (Fang et al. 2003); it was found that the tool tip rigidity of the semicircle-based (D-type) end mills was much higher than that of the two-flute (commercial type) end mills, and the machining quality with the D-type tools was better than that of the triangle-based (**Δ**-type) end mills; D-type end mills with a tapered body were more suitable for micromachining. Currently, the commercially available micromills have the smallest tool diameter of 50 μm. The minimum achievable features depend on machined material, machine tool accuracy, and feature geometry.

**Micro Electro-discharge Machining** Electrical discharge machining (EDM) is a nonmechanical process with which material is removed by spatially and temporally separated electrical discharges between a work piece electrode and a tool electrode. Micro electro-discharge machining is used to manufacture micro-scale features using various mode, such as micro-die sinking electrical discharge machining, micro-wire electrical discharge machining, micro-discharge drilling, micro-electrical discharge milling, micro-electrical discharge grinding, and micro-wire electrical discharge grinding. Compared to micromilling, micro-EDM is an almost force-free process for microstructuring. Even though the process is slower compared to micromilling, the independence of the material's hardness is a big advantage.

*Laser Ablation* Laser ablation is able to generate surface structures in the range of 10–100 μm and surface roughness up to $Ra = 0.5$ μm, based on the optimized energy input for a particular material. Laser ablation is used as a working tool to structure materials by thermal vaporization with well-defined volumes and high lateral precision, which can process metals, ceramics, semiconductor materials, glasses, and polymers.

**Semiconductor Micro-fabrication Processes** Semiconductor micro-fabrication processes, such as X-ray lithography, UV-lithography, dry etching, wet etching, surface deposition/oxidation, electroforming, and molding, are well developed for fabrication of microstructures in MEMS devices and Microsystems. Semiconductor micro-fabrication is also borrowed to manufacture molds for various replication processes or form electrode for EDM sinking. In addition to typical semiconductor materials, such as silicon, it can be also used to pattern photopolymers.

### Micro Replication Processes

Micro replication deals with features down to micrometer scale by using various materials, including metal, ceramic, glass, and polymers. Replication of workpiece geometries is well established within various conventional manufacturing technologies, such as metal forming and plastic injection molding.

**Metal/Ceramic Processing** Metals can be directly formed into a micro cavity by either casting at liquid over melting temperature or by forming at high pressure below melting temperature, or by electroforming using chemical deposition process. A special metal alloy called metallic glasses has no crystalline structure and can be formed using a microstructured silicon master using thermoplastic forming process with surface micro features ranging from micrometer scale to nanometer scale between crystalline temperature and melting temperature with a given time. Metal/ceramic feedstocks can also be used as materials for micro injection molding or hot embossing to form microstructured surfaces, following debinding and sintering processes.

**Polymer/Glass Processing** Polymer materials can be employed to replicate micro patterns from a mold using micro injection molding, hot embossing, casting/curing, etc. Thermoplastic materials can be used to replicate micro-scale patterns over material melting temperature using micro injection molding or blow melting temperature and above glass transition temperature using hot embossing. The replication fidelity of micro features depends on material rheology, surface-to-volume ratio, and adhesion/friction effect during demolding. Micro injection molding and hot embossing are mainstream mass production method for the production of polymeric micro surface structures. Polydimethylsiloxane (PDMS) thermoset material is UV or thermal curable and can be used to replicate micro pattern at room temperature without restrictions of aspect ratio, but it is limited to laboratory use, and adhesion may cause feature damage at demolding process. Glass replicates master mold using a compression molding process over its glass transition temperature. Once the desired deformation is reached, the final shape of the glass elements is determined by the relaxation induced by the forming stress because of its viscoelastic properties around its transition temperature.

## Cross-References

▶ Additive Manufacturing Technologies
▶ Diamond Machining
▶ Electric Discharge Machining
▶ Laser Ablation
▶ Micromachining

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## References

Beke S, Anjum F, Tsushima H, Ceseracciu L, Chieregatti E, Diaspro A, Athanassiou A, Brandi F (2012) Towards excimer-laser-based stereolithography: a rapid process to fabricate rigid biodegradable photopolymer scaffolds. J R Soc Interface 9:3017–3026. https://doi.org/10.1098/rsif.2012.0300

Fang F, Wu H, Liu X, Liu Y, Ng S (2003) Tool geometry study in micromachining. J Micromech Microeng 13:726–731. https://doi.org/10.1088/0960-1317/13/5/327

Gittard SD, Miller PR, Boehm RD, Ovsianikov A, Chichkov BN, Heiser J, Gordon J, Monteiro-Riviere NA, Narayan RJ (2011) Multiphoton microscopy of transdermal quantum dot delivery using two photon polymerization-fabricated polymer microneedles. Faraday Discuss 149:171–185. https://doi.org/10.1039/c005374k

Müller T, Piotter V, Plewa K, Guttmann M, Ritzhaupt-Kleissl H-J, Hausselt J (2009) Ceramic micro parts produced by micro injection molding: latest developments. Microsyst Technol 16:1419–1423. https://doi.org/10.1007/s00542-009-0992-1

Qin Y (2010) Micro-manufacturing engineering and technology. William Andrew Publishing, Boston, pp 1–23

## Micro-turning

▶ Micromachining

## Microwave Radiation

James Lucas
Department of Electrical Engineering and Electronics, University of Liverpool, Liverpool, UK

### Synonyms

Applications; Microwave sources; Storage; Transportation

### Definition

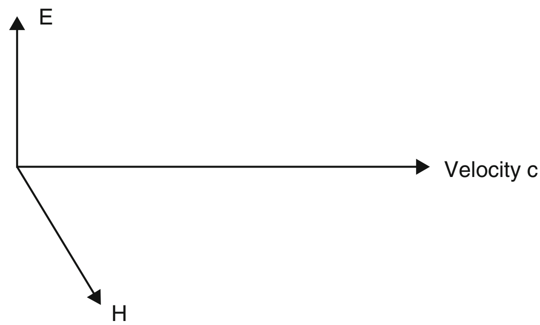
Microwaves are electromagnetic waves having frequencies between 300 MHz (radio waves) and 300 GHz (infrared waves) within the electromagnetic spectrum.

The electromagnetic plane wave propagation is shown in Fig. 1 having a characteristic impedance within free space.

$$Z_o = E/H = 120\pi\Omega(377\Omega)$$

E and H are at right angles, and in discussing microwaves, it is usual to refer mainly to the electric E field since the location and magnitude of the magnetic H field are readily deduced from the E field information and direction of propagation. The wave travels with a velocity $c = 3 \times 10^8$ m/s in free space and a velocity $c = 3 \times 10^8/\sqrt{\varepsilon_r \mu_r}$ where $\varepsilon_r$ is the relative permittivity and $\mu_r$ the relative permeability, when propagating through dielectric/magnetic materials. The propagation wavelength is $\lambda = c/f$, where f is the microwave frequency.

Hence, the microwave wavelength varies between 1 m and 1 mm as the frequency increases. Each frequency range is referred to by its band designation as listed in Table 1. The microwave power (P) transmitted per unit area is given by Poynting's vector as $P = EH = E^2/Z_o$.




**Microwave Radiation, Fig. 1** The EM plane wave in the free space

**Microwave Radiation, Table 1** Letter designation of microwave bands by the Radio Society of Great Britain (RSGB)

| Band | Frequency range GHz | Source |
|---|---|---|
| S, C | 2–4, 4–8 | RSGB |
| X, Ku | 8–12, 12–18 | RSGB |
| K, Ka | 18–26.5, 26.5–40 | RSGB |
| U | 40–60 | RSGB |
| V, W | 46–56, 50–100 | US Navy |

## Theory and Application

### Theory

#### Microwave Sources

The major microwave power sources are given in Table 2 (Roddy 1986).

Devices 1–4 are all vacuum tube devices using an electron beam to transfer dc energy into microwave energy. Magnetrons are used in the process industry but do not operate at frequencies above 10 GHz. Other devices such as traveling wave tubes, klystrons, and gyrotrons are also available but have so far not been taken up by the process industry. The traveling wave tubes and klystrons are mainly used by the communications industry because they operate as amplifiers and do not normally produce high powers. The gyrotron, on the other hand, is capable of producing very high power at high frequencies but is very expensive (uses a superconducting magnet), complicated to manufacture, and does not have the reliability to operate in an industrial environment. Solid-state devices generate very low-power microwave sources over the full microwave spectrum (Ws at low frequencies and μW at higher frequencies).

#### Microwave Transportation

Microwave equipment and techniques share roughly the same dimensions as the radiation wavelength (Sadiko 1994). Microwaves travel within metallic rectangular or circular tubes called waveguides. The wave is internally reflected from the waveguide walls and sets up a regular E field and corresponding H field wave pattern within the waveguide. Focused nodes exist across and along the waveguide with a separation of $\lambda_g/2$ where $\lambda_g$ is the EM wave wavelength within the guide.

The guide wavelength ($\lambda_g$) is related to the free space wavelength ($\lambda$) and the tube dimensions as given by Eq. 1.

$$1/\lambda_{g^2} = 1/\lambda^2 - 1/\lambda_{c^2} \quad (1)$$

$\lambda_c$ is referred to as the cutoff wavelength and represents the lowest frequency capable of propagating down the waveguide.

The radiation pattern over the cross section of the waveguide takes up a series of modes designated by m and n. Figure 2 illustrates the location of these modes for both rectangular and circular waveguides. The propagated wave down the waveguide is denoted by $TE_{mn}$. For the rectangular waveguide, the main propagation mode is m = 1 and n = 0, and the wave is referred to as the $TE_{10}$ mode. The structure of the microwave energy within the waveguide for the $TE_{10}$ mode is shown in Fig. 3. The end view shows the E and H fields for the m = 1 and n = 0, while the side and top views show the periodic structure of $\lambda_g/2$. The cutoff wavelength for the $TE_{10}$ mode is given by Eq. 2.

$$1/\lambda_{g^2} = 1/\lambda^2 - 1/(2a)^2 \quad (2)$$

where a is the larger internal width of the waveguide.

Microwaves can be launched into the waveguide by using a coaxial cable. Electrostatic coupling employs a short probe which behaves as an antenna, while electromagnetic coupling is possible by using a small closed loop as shown in Fig. 4. The power (P) propagated per $m^2$ down the waveguide is given by Eq. 3.

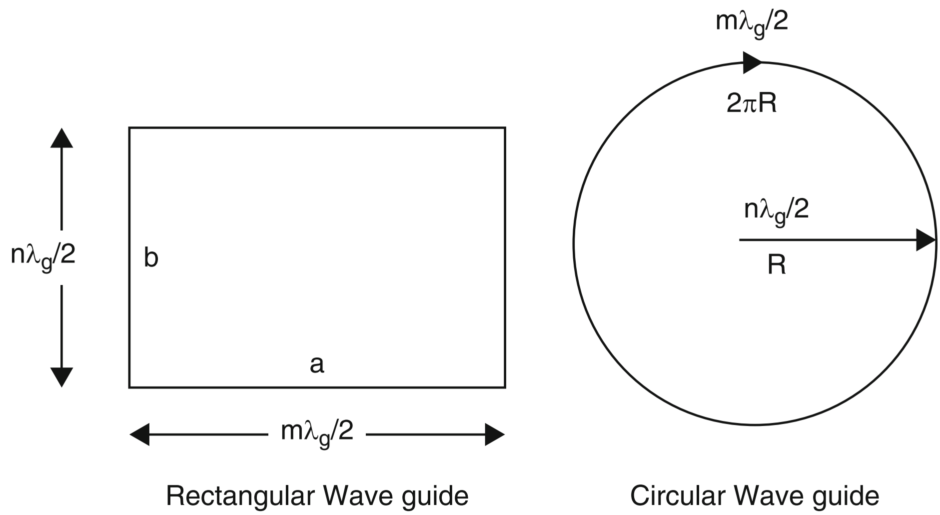
$$P = E^2/Z_g \text{ with } Z_g = 120\pi\lambda_g/\lambda \quad (3)$$

Waveguides are available in a wide range of sizes, and a few have been selected to illustrate the range and their corresponding WG

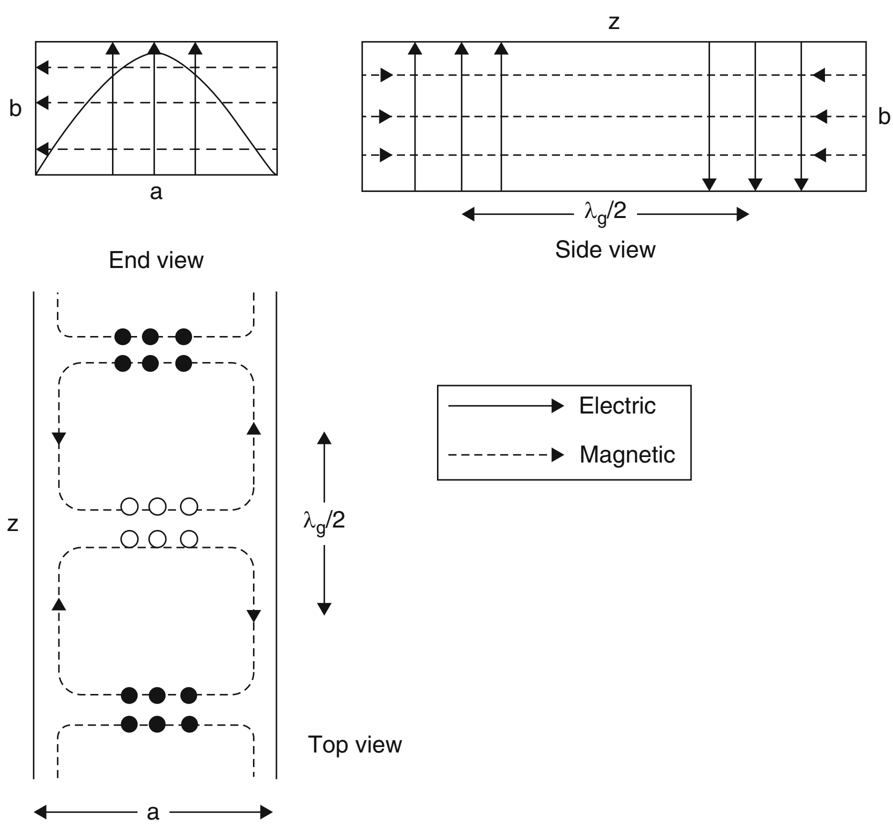
**Microwave Radiation, Table 2** Microwave sources

| No | Source | Frequency range | Typical maximum power |
|---|---|---|---|
| 1 | Magnetrons | 300 MHz–5 GHz | 10 kW |
| 2 | Klystron | 300 MHz–50 GHz | 5 kW |
| 3 | Traveling wave tube | 300 MHz–50 GHz | 5 kW |
| 4 | Gyrotron | 20 GHz–300 GHz | 1 MW (pulsed) |
| 5 | Solid-state devices | 300 MHz–300 GHz | 1 W |

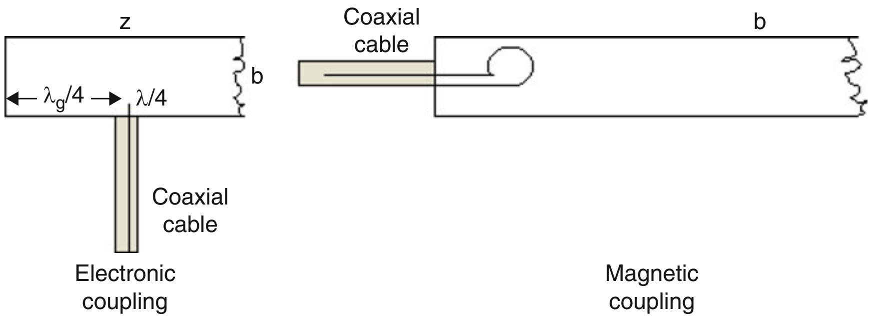
M




**Microwave Radiation, Fig. 2** The conditions required to produce the waveguide propagation modes




**Microwave Radiation, Fig. 3** The $TE_{10}$ mode within the waveguide




**Microwave Radiation, Fig. 4** Launching microwaves into a waveguide

**Microwave Radiation, Table 3** Technical data for standard rectangular guides

| UK WG designation | Internal guide dimensions a (mm) b(mm) | | $TE_{10}$ cutoff frequency (GHz) | $TE_{10}$ operating range (GHz) | Attenuation (dB/30 m) | Maximum power rating kW |
|---|---|---|---|---|---|---|
| 10 | 72.1 | 34.0 | 2.08 | 2.60–3.95 | 0.555 | 2800 |
| 16 | 22.9 | 10.2 | 6.56 | 8.20–12.4 | 3.24 | 250 |
| 20 | 10.7 | 4.3 | 14.08 | 18.0–26.5 | 10.9 | 52 |
| 25 | 3.61 | 1.87 | 39.9 | 50.0–75.0 | 44.7 | 8 |
| 27 | 2.54 | 1.27 | 59.0 | 75.0–110 | 80.7 | 3.8 |

designation for the $TE_{10}$ mode. These have been given in Table 3. As the microwave frequency increases, the dimensions of the guide decrease. The maximum power capable of being transmitted down the guide also decreases, but the attenuation of the transmitted power increases. Microwave applications require the interaction of microwaves with materials (or objects). Carrying out such applications requires the microwave energy to either be stored within a resonance cavity containing the material or propagated toward the material (or object) from an antenna.

### Cavity Resonators

Fields can exist in regions entirely bounded by conducting walls called cavities. The cavities may be rectangular or circular in shape and behave similar to resonant circuits. If a small loop is coupled into a cavity and excited by an oscillator, very large fields can exist in the cavity at certain fixed frequencies. These are referred to as cavity modes and are basically waveguide modes since a resonant cavity can be constructed by shorting a length of waveguide (rectangular or circular) with metal end plates. A standing wave pattern will exist in the cavity.

The cavity modes are specified by the two basic subscripts m and n used for rectangular waveguides. In addition, a third subscript p designates the number of half wavelengths along the cavity length $p = 2l/\lambda_g$.

Hence, we have $TE_{mnp}$ and $TM_{mnp}$ modes for rectangular cavities.

### Antenna

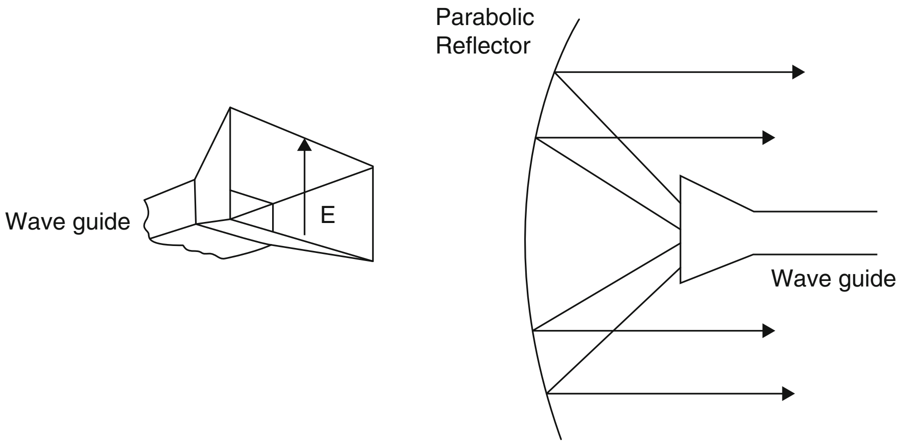
Propagation through the atmosphere uses individual horn antenna or combined horn and parabolic reflectors as shown in Fig. 5 (Monaco 1989). The parabolic reflector initially emits an approximately parallel beam. The radiation strength of the E field at a distance (z) is given by:

$$E = E_o \sin(\omega t - \beta z)e^{-az} \quad (4)$$

where $\beta = 2\pi/\lambda$ and $\alpha$ = attenuation coefficient.

### Applications

There are many important applications of microwaves. Microwaves are either contained within a




**Microwave Radiation, Fig. 5** Horn antenna for transmission of microwaves

cavity or are transmitted in straight-line paths between a source and a receiver.

### Microwave Heating

A kitchen microwave oven uses magnetron-generated microwaves at a frequency 2.45 GHz to cook food by causing dielectric heating of water and fats content within food, fruit, and vegetables. Microwave heating is also used for melting, drying, and curing of products, especially at 896 MHz. The melting of glass within an 896 MHz tuned cavity has been developed for encasing low-level radioactive waste (BNFL). Offline regeneration of diesel particle filters (DPF) using 2.46 GHz microwaves has been carried out by dielectric heating of the DPF within a tuned cavity. The carbon particulates are oxidized to both CO and $CO_2$ by gently flowing air through the pores (Lucas 2005).

### Microwave Plasma

Microwave plasma can be generated in a gas at both low pressure and high pressure by allowing electrons to obtain energy from the microwaves. The condition is that the unbound electrons within the gas obtain the gas ionization energy $eV_i$ during the time between molecular collisions.

Low-pressure plasmas using gas pressures <1 mbar are easy to attain within a cavity. Such plasmas are used by the semiconductor processing industry for reactive ion etching and plasma-enhanced chemical vapor deposition (PECVD).

High-pressure plasmas are obtained by enhancing the electric field within a microwave cavity and are used for material processing including metal cutting and ceramic coating of metals (Lucas 2005).

A long-term research project is the use of high-power (MW), 110 GHz–170 GHz microwaves from gyrotrons to create a plasma suitable to generate a fusion reactor for electrical power generation.

The rapid curing of epoxy glues using microwaves allows electronic chips to be glued to smart cards in an automated process (Lucas 2005).

### Food Processing

A resonant cavity has been used to excite and provide power to a low-pressure mercury vapor lamp to produce UV radiation with 154 nm and 180 nm wavelengths. The conversion efficiency of microwave power into UV light power is very efficient at 80% (Lucas 2005). This UV is used for germicidal activity within the food and drinks industry. By irradiating food with UV before MAP, packaging doubles the shelf life. Likewise, a similar effect has been obtained with Turkish beers (Boza).

### Microwave Chemistry

The most widespread use of microwaves in chemistry occurs in analytical laboratories primarily for sample preparation. Applications include drying,

**Microwave Radiation, Table 4** Enhanced reaction rates by microwave heating

| Rate constants ($\times 10^3$) | | | | |
|---|---|---|---|---|
| Temperature | Xylene | | Ethanol | |
| T°C | Microwave heating | Conventional heating | Microwave heating | Conventional heating |
| 60 | 5.7 | 2.2 | 6.9 | 4.9 |
| 80 | 12.2 | 3.7 | 12.9 | 8.6 |

extractions, acid dissolution, decomposition, and hydrolysis. When using microwave processing, a number of fundamental organic reactions have shown accelerated rates and increased yields over conventional techniques (Loupy 2002). Microwave energy penetrates into the interior of the sample without relying on conduction from a heated surface as required in conventional heating methods. Table 4 lists the reaction rates for the Diels-Alder reaction and shows the acceleration when heated by microwaves.

### Personal Security Screening Systems

These operate with the highest microwave frequencies. PNNL has recently developed a standoff, three-dimensional imaging technique and prototype that operates with mm waves (Lesurf 1990) near 350 GHz. It scans personnel at distances up to 20 m within a period of 20 s. It has a spatial resolution of 1 mm and a depth resolution of 2 mm. Hence, it is able to reveal concealed items beneath the clothing.

### Microwave Safety

Microwaves are of a nonionizing character. They do not have the energy to cause chemical changes in substances as would happen in the case of radioactivity. Microwaves only become a hazard with high microwave powers. The principal danger of microwaves is that body tissue can be affected in a similar way that food is and microwaves can cause burns, eye cataracts, and other injuries. This occurs because the surface is unable to be cooled by the surrounding fast enough.

### Additional Important Applications

These include communications, radar, radio astronomy, satellite navigation, and weather forecasting.

## References

Lesurf J (1990) Optics, devices and systems. Adam Hilger, Bristol
Loupy A (ed) (2002) Microwaves in organic synthesis. Wiley – VCH, Weinheim
Lucas J (ed) (2005) MICROPRO: final report. EC Project No. G5RD-CT-2001-0056
Monaco F (1989) Introduction to microwave technology. Merrill Publishing, Columbus
Roddy D (1986) Microwave technology. Prentice-Hall, Englewood Cliffs
Sadiko MNO (1994) Elements of electromagnetics. Sanders College Publishing, Rochester

# Microwave Sources

▶ Microwave Radiation

# Mill

▶ Machine Tool

# Milling Machine

▶ Machine Tool

# Milling of Titanium

Markus Groppe
Sandvik Coromant GmbH, Düsseldorf, Germany

## Definition

Milling summarizes the machining processes of square shoulder-, face-, profile-, and slotmilling.

Titanium means titanium alloys (alpha and beta) used as a high strength, light weight, and corrosion resistant material e.g., in aerospace, medical, and automotive applications.

## Theory and Application

### Milling of Titanium

The scale of difficulty to machine titanium alloys in industrial production increases with each succeeding year. The reason for the increasing use is the special characteristics of this material. Titanium has many positive features which make it interesting for the design engineers. Its excellent mechanical strength in combination with a low density has led to an even higher use of this material in the aerospace industry. As a result, titanium is also now being used to a greater extent in the automotive sector. Titanium alloys are very corrosion resistant and well tolerated by human tissues, making them ideal for the medical and dental industries. Another large application area is the chemical industry and offshore-operation.

Table 1 shows the most important material properties of the most widely used titanium alloys TiAl6V4 compared to steel Ck45 (Coromant 2010).

The positive mechanical properties lead to high machining forces and higher demands on the cutting edge. When it comes to the cutting process, a critical factor is its very low thermal conductivity. For machining steel, a large amount of the mechanical energy resulting from the cutting process can be dissipated with the chips or the work piece. Due to the poor conductivity of titanium, the heat is directly conducted into the cutting edge and the tool and leads to a very high thermal load. Further characteristics of this material which have to be considered for the cutting process are the low modulus of elasticity and the high tensile strength which allow only a minor plastic deformation. The material tends to be resilient, thus putting high loads on the flank face. Additionally, the formation of segmented chips leads to a shorter contact length and high loads on the cutting edge (Corduan et al. 2003; Koenig et al. 1990).

These special characteristics of titanium require a precisely adjusted machining process starting with the choice of a suitable tool and process parameters as well as consideration of other factors such as machine tool and coolant supply.

**Milling of Titanium, Table 1** Material properties of TiAl6V4 versus steel Ck45

| Material properties | TiAl6V4 | Ck45 |
|---|---|---|
| Density (g/cm$^3$) | 4.43 | 7.87 |
| Modulus of elasticity (GPa) | 108–113 | 210 |
| Tensile strength $R_m$ (MPa) | 900–1180 | 630 |
| Elastic limit $R_{p0,2}$ (MPa) | 830–1030 | 390 |
| Breaking elongation A5 (%) | 8–15 | 14–17 |
| Hardness (HB) | 320 | 170 |
| Heat capacity $c_p$ (J/kgK) | 500–567 | 486 |
| Heat conductivity $\lambda$ (W/mK) | 6.5–7.56 | 51.9 |

### Requirements on Cutting Tools

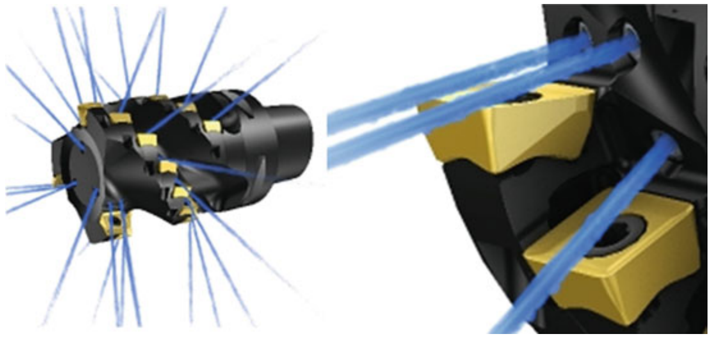
The high loads for machining titanium require the application of tools with maximum stability. At the same time, very sharp cutting edges and geometries are needed to keep the cutting forces low. Moreover, the cutting edge is exposed to high thermal load so that the chosen cutting tool material has to withstand high forces in different direction.

This situation requires specialized solutions with optimized insert geometries and substrate/coating composition. Figure 1 shows a tool especially designed for the machining of titanium.

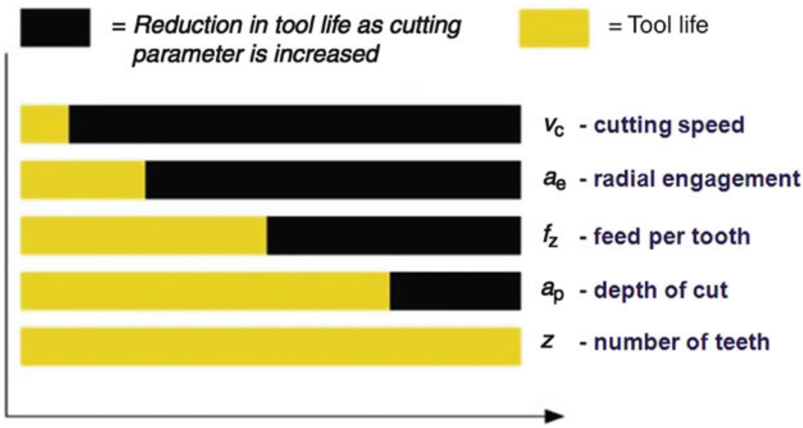
This long edge milling cutter has a patented interface to secure axial and radial insert clamping with four cutting edges. This system allows a stable support in combination with large chip spaces. Thus, the chip flutes can be designed for an optimized chip evacuation needed to achieve high metal removing rates.

### Coolant Support

When machining titanium, the high thermal loads only allow the application of reduced cutting data. But in order to obtain a productive cutting process, a large amount of the thermal energy has to be dissipated with the help of an optimized



**Milling of Titanium, Fig. 1** Long edge milling cutter for titanium machining (Coromant 2010)




**Milling of Titanium, Fig. 2** Cutting parameter during titanium milling (Coromant 2010)



coolant system. The new titanium cutter has a special designed coolant supply with nozzles offering an improved chip evacuation and intensive cooling of the cutting edge. In contrast to conventional tooling, this concept leads to considerably elevated tool life. This effect can even be increased with high pressure coolant supply.

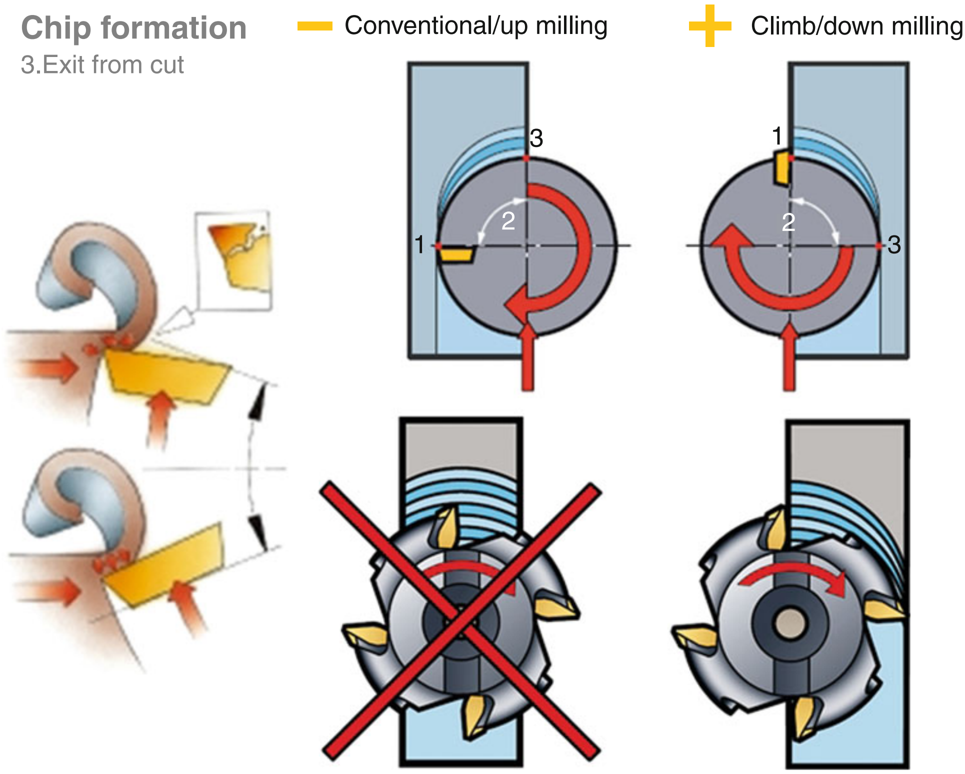
## Adjusting Cutting Data

Beside the tool properties, the process parameter have a strong influence on tool life. Figure 2 shows an overview of the influence of the cutting parameter in milling titanium. The black bar indicates the estimated reduction in tool life when increasing the corresponding parameter. Most influence has the cutting speed $v_c$, which can be used to "control" the wear almost proportionally. The width of cut $a_e$ determines the time of engagement for the cutting edge and thus the time of the insert exposed to the thermal load. It is also suggested to keep the chip thickness and feed rates low to avoid excessive stress on the cutting edge. Only two factors are left to increase productivity: Milling should be performed with as many cutting edges as possible to allow productive feed rates. In addition, titanium milling should always include large cutting depths to achieve a high material removal rate but also to obtain an even wear and an effective utilization of the full cutting length.

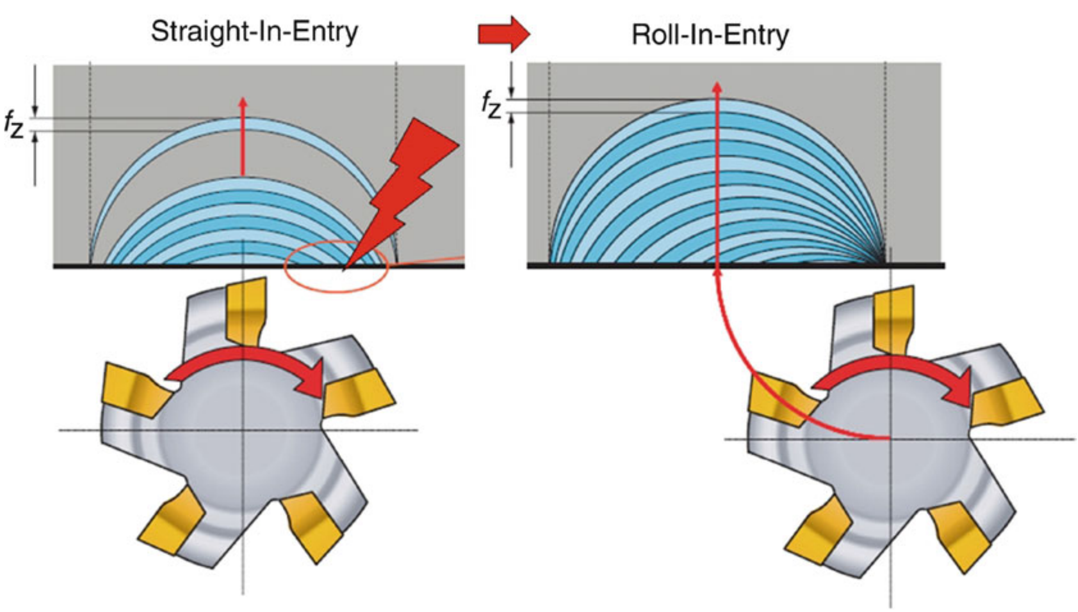
## Selecting the Correct Machining Strategy

The high tensile strength, the low modulus of elasticity, and the hardness of titanium alloys require a special consideration of the milling strategy. Especially for the machining with coated carbide inserts, it is essential that the chip thickness on the exit of the cutting edge is reduced to a minimum in order to avoid tensile stress occurring when shearing off the chips at the cutting edge (see Fig. 3). Up-milling as well as positioning of the tool in the center should be avoided.

Even a Straight-In-Entry creates a thick chip on exit (see Fig. 4) which can lead to insert chipping and vibration. The Role-In-Entry method helps to




**Milling of Titanium, Fig. 3** Machining strategy (Coromant 2010)

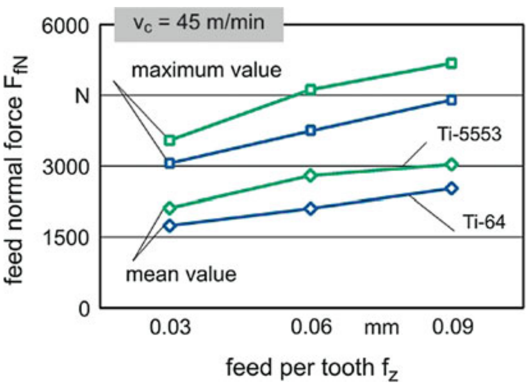



**Milling of Titanium, Fig. 4** Roll-In-Entry method avoids thick chip on exit (Coromant 2010) minimize the chip thickness on exit allowing for secure process to be set up (Dege 2010).

### Milling of b-Titanium Alloys

The development of new titanium alloys focuses mainly on β-titanium alloys which have an even higher tensile strength compared to TiAl6V4 (Ti-64). The landing gear of an Airbus A380, for example, consists of TiV10Fe2Al3. The alloy TiAl5V5Mo5Cr3 (Ti-5553) (Panza-Giosa et al. 2006) offers an even higher tensile strength in combination with improved cast and age hardening. This material presents an even increased potential for savings in weight while offering improved cast and age hardening characteristics. Milling of Ti-5553 is an even more demanding process compared to machining Ti-64.

The process forces represent the mechanical loads on the cutting tools and the related deflection between tool and workpiece. Figure 5 shows a comparison of the machining forces for milling two titanium alloys (Denkena et al. 2010).



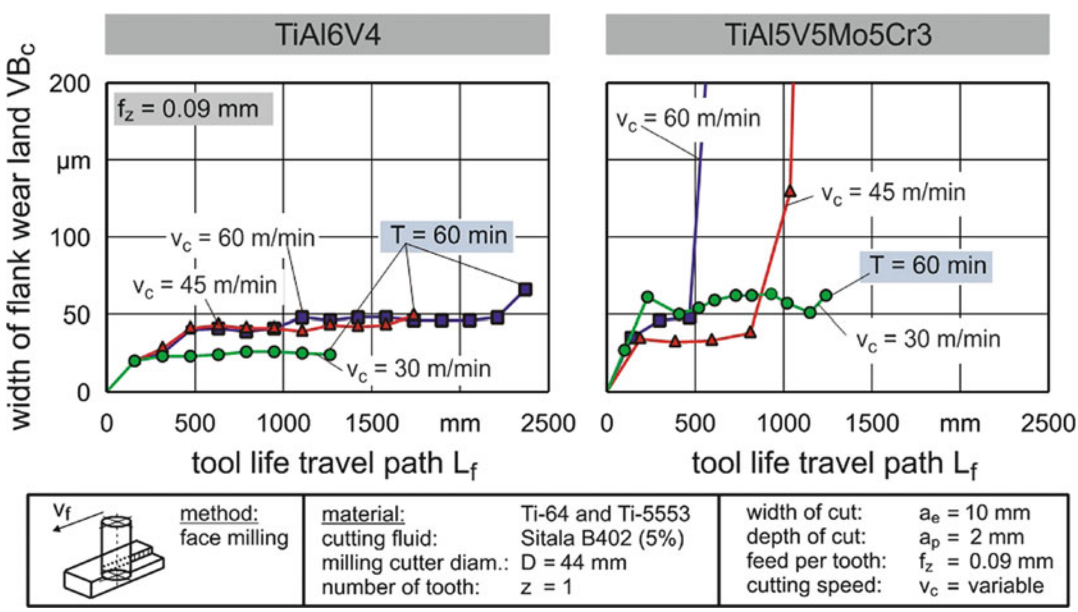

**Milling of Titanium, Fig. 5** Influence of the feed per tooth on the normal feed force (Denkena et al. 2010)

The highest cutting forces occur while machining down-milling normal to the feed direction. Obviously, the cutting force is significantly higher when milling Ti-5553 as compared to Ti-64.

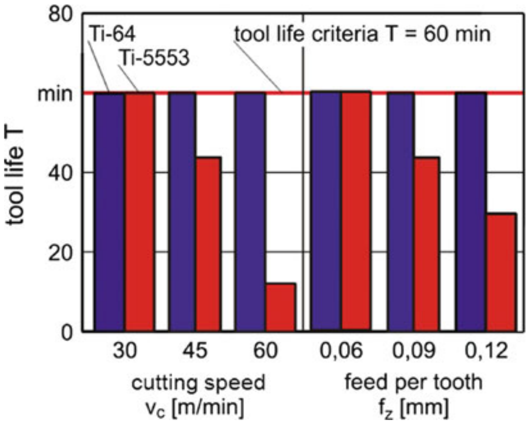
The internal coolant supply has a significant influence for milling titanium. The tool applied for the investigation features internal coolant supply with exit nozzles directed to the cutting edge. The tool life being reached with a reference speed $v_c = 45$ m/min and feed per tooth $f_z = 0.06$ mm compared to conventional external coolant supply (Fig. 6).

For the external coolant supply, the tool applied in Ti-5553 will fail after half of the calculated tool life. For machining in Ti-64, however,






**Milling of Titanium, Fig. 6** Influence of the cooling strategy on tool life (Denkena et al. 2010)




**Milling of Titanium, Fig. 7** Influence of the process regulating variables on tool (Denkena et al. 2010)

the tool life criterion of T = 60 min is met. Additional internal coolant supply shows no additional benefit on wear progress.

The influence of cutting speed and feed per tooth on tool life is shown in Fig. 7. The mounted inserts have reached the end of tool life criterion in Ti-64 but fail for the higher cutting speeds after a reduced feed path. This can be attributed to the increased friction-effects between tool and workpiece, resulting from both higher toughness as well as hardness of the Ti-5553 against the reference alloy. In addition it is shown that with an increased feed per tooth which can be applied in Ti-64 fulfilling the tool life criterion, this is not possible for machining Ti-5553. The wear mechanism of the tools hereby is cutting edge chipping due to very high loads on the cutting edge.

## Summary

These investigations of machining titanium have shown that numerous requirements have to be fulfilled for this technologically complex machining process. Particularly, in the case of machining β-titanium alloys Ti-5553, high chemical and thermal loads on the tools are a critical factor. Only an adjusted cooling strategy and suitable cutting data, particularly a reduced cutting speed, and a low chip thickness in combination with an adapted programming strategy ensures a reduced wear and a safe process.

For titanium milling applications, increased effort should be spend at the start for planning and preparation of the machining process. A stable machine tool, very rigid tool holders, and reduced tool overhangs should be applied. If machining with dedicated tools and carefully adapted process parameters, even titanium alloys can be machined with a high productivity.

## Cross-References

- ▶ Chip-Forms, Chip Breakability, and Chip Control
- ▶ Cutting Fluid
- ▶ Cutting, Fundamentals
- ▶ Machinability
- ▶ Wear Mechanisms

## References

Corduan N, Himbert T, Poulachon G, Dessoly M, Lambertin M, Vigneau J, Payoux B (2003) Wear mechanisms of new tool materials for Ti-6Al-4 V high performance machining. CIRP Ann Manuf Technol 52(1):73

Coromant S (2010) Technical guide 2010. Sandvik Tooling, Düsseldorf

Dege JH (2010) Zerspanung von Titanlegierungen – Voraussetzungen für das HPC-Fräsen. Vortrag, DGM-Fortbildungsseminar: Titan und Titanlegierungen (Cutting of titanium alloys – pre-conditions for high-performance-cutting. Oral presentation at DGM-advanced-training-course: titanium and titanium alloys), Leibniz Universität Hannover, Institut für Fertigungstechnik und Werkzeugmaschinen (IFW), Köln, 17 März 2010

Denkena B, Dege JH, Groppe M, Grove T (2010) Zerspanbarkeit von β-Titanlegierung: Vergleich von "Ti-5553" und "Ti-64" (Machinability of β-titanium alloy Ti-5553 vs. Ti-64). VDI-Z Special Werkzeuge 2010:24–27

Koenig W, Cronjaeger L, Spur G, Toenshoff HK, Vigneau M, Zdeblick WJ (1990) Machining of new materials. CIRP Ann Manuf Technol 39(2):673–681

Panza-Giosa R, Embury D, Wang Z (2006) Microstructure evolution and mechanical properties in Ti-5Al-5V-5Mo-3Cr after solution heat treatment and ageing in the alpha-beta range. In: Seminar Roque, 2006. http://coursenotes.mcmaster.ca/701-702_Seminars/2006-2007/702_Roque_Panza-Giosa_Sept_20_07.pdf. Accessed 10 June 2013

## Milling Spindle

► Spindle

## Minting

► Embossing

## Mock-Up

► Prototyping

## Modal Analysis

► Structural Analysis

## Modeling in Cutting

P. J. Arrazola
Faculty of Engineering, Manufacturing Department, Mondragon Unibertsitatea, Arrasate-Mondragon, Gipuzkoa, Spain

### Synonyms

Simulation of Machining Processes

### Definition

**Modeling of machining processes** is the competence of predicting the influence of input cutting parameters on output variables such as (i) fundamental variables and (ii) industrial relevant outcomes. Fundamental variables are forces, temperatures, strains, strain rates, stresses, and pressures. Industrial relevant outcomes include tool life, surface roughness, surface integrity, distortion, stability, and burrs.

In order to predict the abovementioned outputs, different modeling approaches can be employed. For years, analytical and empirical models were the most commonly used. Recently, numerical and artificial intelligence (AI)-based methods are gaining relevance with the increase in computing power. The reason for this is the capability of computers to deal with complex problems such as tool–chip contact and material nonlinearities.

### Theory and Application

#### Modeling Overview

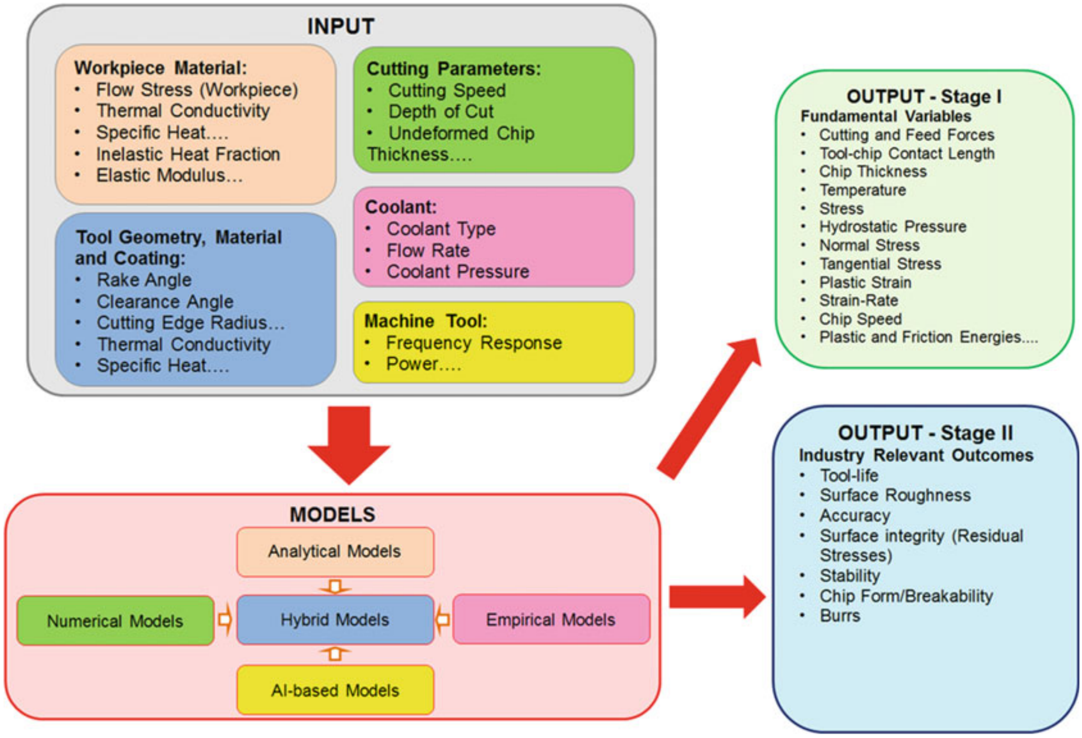
During machining, very complex mechanical, thermal, and chemical phenomena occur. Due to this, and although several significant advances have been made on the knowledge of cutting processes, there are still many issues that remain not well understood. That is, tool-life, surface finish, subsurface integrity, chip-form/chip breakability, burr formation, part accuracy, etc.

In recent years it has been shown that modeling can provide a more comprehensive and, in some cases, complementary approach to experimental methods (Arrazola et al. 2013). Modeling offers the capability to predict what could happen during the material removal process. This enables the design and modification of process input parameters beforehand in order to reduce or eliminate problems that may arise during machining operations. These predictive models could be (i) integrated into process planning systems to improve productivity and enhance product quality and (ii) used also in adaptive control for machining processes, reducing, and/or eliminating trial-and-error approaches.

Figure 1 summarizes the basic modeling structure, where three main parts can be observed: (i) input parameters, (ii) models, and (iii) output parameters.

#### Scales in Modeling

Depending on the problem to be studied, modeling of machining processes can be focused on different scales (Fig. 2):




**Modeling in Cutting, Fig. 1** Basic scheme for modeling of machining processes

- Macroscale: Models that take into account machine tool, workpiece, and tool including their fixture system and toolholder (Urresti et al. 2009). In this scale prediction of distortions is the main goal.
- Mesoscale: Models which consider the area where the chip is formed. With this scale it is possible to predict cutting forces, tool temperatures, burr formation, tool wear, and changes in the microstructure (Klocke and Frank 2006; Umbrello et al. 2010).
- Microscale: Models that study the influence of the microstructure, grain boundaries, and crystalline plasticity during chip formation (Umbrello et al. 2010; Abouridouane et al. 2012; Zhang et al. 2012). In this scale prediction of machinability rates and material damage is the main goal.

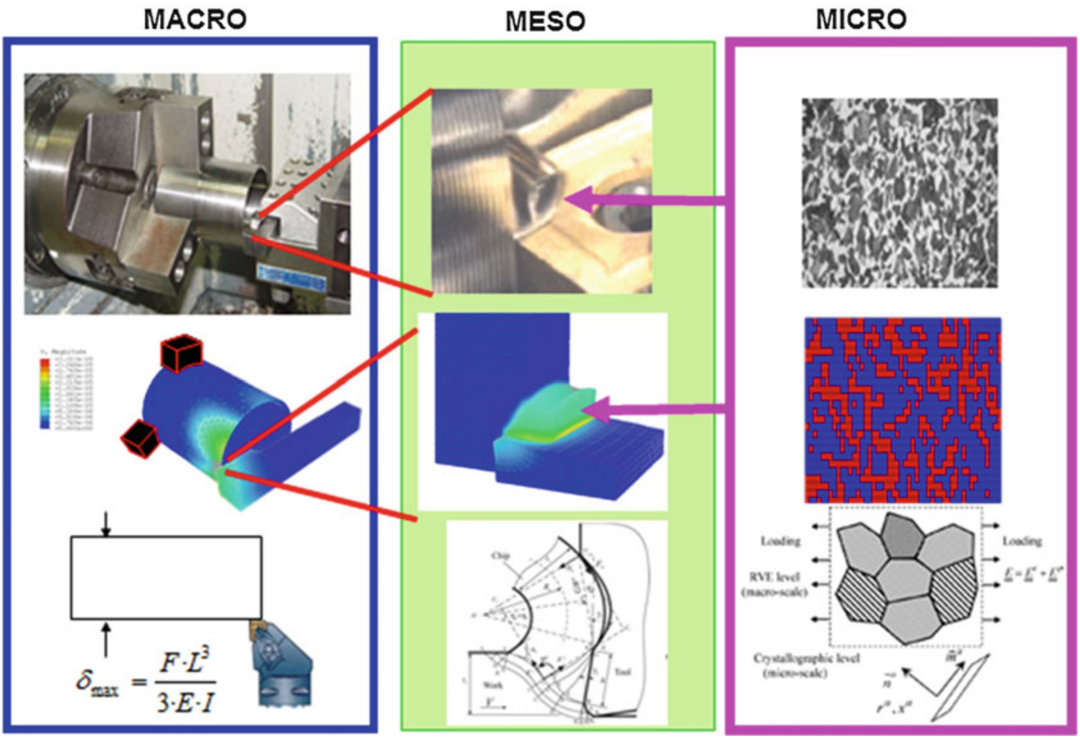
However, issues like surface integrity may require more than one scale. For example, in turning it is necessary to simulate more than one revolution in order to obtain an accurate residual stress profile (Valiorgue et al. 2012). In such cases where more than one scale is needed, hybrid modeling could be a promising strategy.

The scale of the analyzed phenomena affects the model minimum specifications. In general it could be said that, while in microscale, a fully coupled chemical thermomechanical model is desirable, in mesoscale a coupled thermomechanical model is necessary, and in macroscale an uncoupled model could be enough.

## Types of Modeling

Models can be classified in several types:

- Analytical models, including slip-line models, can directly predict cutting forces, friction in the local cutting zones, stresses, residual stresses, strains, strain rates, and temperatures. However, the complexity of the process still makes it difficult to predict analytically the principal industry-relevant outcomes, since they are mainly developed for 2D analysis (Wang and Jawahir 2007).



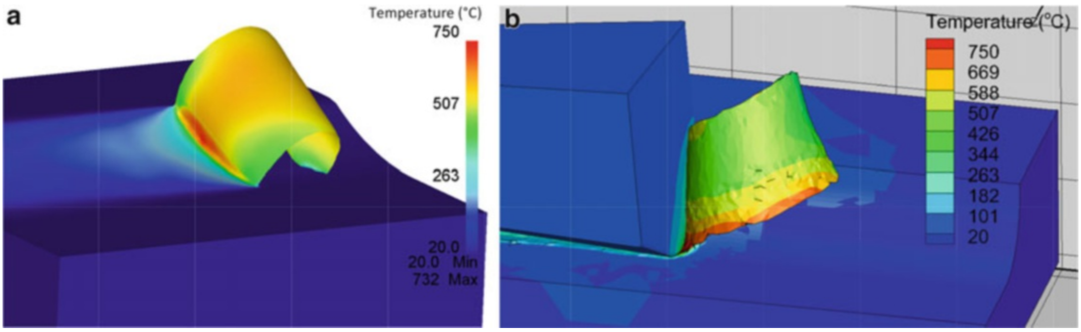

**Modeling in Cutting, Fig. 2** Scales in modeling of machining (Wang and Jawahir 2007; Zhang et al. 2012)



- Numerical models (finite element modeling (FEM), finite difference methods, meshless techniques, etc.) are based on continuum mechanics. They are able to predict nonlinear problems more effectively than analytical models, and thus they can take into account issues such as complex tool–chip contact, and material behavior. The computational cost and reliable material data are the major limitations of these models. Although there are some developments in 3D, most of the progress has been made in 2D. Due to the extensive computational demands, it was not until the late 1990s that numerical methods became a useful and practical tool (Klocke and Frank 2006).
- Commercial software packages exist in the market. They provide an interface to facilitate the entry of process parameters, without the necessity for the end user to understand the mathematical theory of finite element method (see Fig. 3).
- Empirical models are the simplest approach and are widely used in the absence of other meaningful models. Empirical models often utilize statistical methods and are only valid for the ranges of the experiments conducted. They are practical and able to estimate industrially relevant outcomes. The major drawback is that they need extensive experimentation, and thus their development becomes time-consuming and costly.
- Hybrid modeling is based on the combination of some of the analytical, numerical, empirical, or artificial intelligence (AI)-based methods. They can be used to predict industry-relevant process performance measures, taking the advantages of each method and searching for a better and quicker prediction (Valiorgue et al. 2012).

### Current State of the Art

To the present day, modeling of orthogonal cutting continues to dominate research activities in




**Modeling in Cutting, Fig. 3** DEFORM 3D. Example of two different software analysis results: (**a**) Inconel turning ($Vc = 30\ m \cdot min^{1}$, $f = 0.4\ mm \cdot rev^{1}$), (**b**) AdvantEdge 3D. Titanium turning ($Vc = 55\ m \cdot min^{1}$, $f = 0.15\ mm \cdot rev^{1}$)

machining modeling due to its simplicity. Most research focuses on calculating the fundamental physical variables in the chip formation process in orthogonal cutting conditions (2D) (Stage I in Fig. 1), while the end goal is prediction of industry-relevant outcomes in 3D (Stage II in Fig. 1).

Understanding the interactions between input parameters and the resulting fundamental process variables (Stage I in Fig. 2) is an active research area. Obtaining a universal and quantitatively accurate chip formation model remains a major challenge. Thus, Stage II outcomes are the end goal, while efforts in predicting Stage I variables still continue.

### Model Parameter Identification

The fact that the results obtained are often uncertain is due to the uncertainty of input parameters, one of the major shortcomings in modeling so far. Modeling of chip formation requires the values of several parameters to model the different phenomena appearing in the process, e.g., (i) flow stress, conductivity, specific heat and inelastic heat fraction for material behavior, and (ii) friction, thermal conductance, and heat partition coefficients for tool–chip contact behavior. At the macroscale bulk residual stress values are required.

To obtain accurate results, these parameters should be identified in similar conditions to those in machining, i.e., high strain (1–4), strain rate ($10^4\ s^{-1}$ –$10^6\ s^{-1}$), temperature (1000–1400 K), and temperature rate ($10^6$–$10^7\ K \cdot s^{-1}$). However, in most cases (e.g., workpiece flow stress and tool–chip friction identification), it is a difficult task because the available experimental equipment is not able to reproduce these conditions.

An alternative approach is to use inverse identification. This is a combination of machining tests and numerical modeling, so as to obtain a corrected law, but this approach may not always result in a single solution (Özel and Davim 2009), unless the appropriate methodology is employed.

### Prediction of Fundamental Variables (Stage I)

Certain fundamental physical variables, such as forces, temperatures, stresses, strains, and strain rates in 2D and 3D, can be predicted with mechanistic, analytical, and numerical models (Arrazola et al. 2013). Although it is still not possible to measure some variables (e.g., stresses at the cutting tool), FEM does provide quantitative values, which offer a useful insight. The prediction of thermal and stress fields by the use of analytical slip-line models, finite different methods, and numerical models is a key issue in machining for developing cutting tools or components with longer fatigue life.

### Predictive Performance Model Development (Stage II)

**Chip Formation** The prediction of chip geometry has been a key research area in recent years which chip breakability of great interest to industry. Although analytical, empirical, and 2D and 3D FEM models have been developed, chip breakability prediction is based in most cases on empirical models (Fang et al. 2001). The impact of serrated chip formation on chip morphology has also been analyzed by the use of finite element methods (Sima and Özel 2010).

**Surface Integrity** Residual stresses of machined components directly affect fatigue life. Many studies have been carried out on the machining process of Ti- and Ni-based alloys with the aim of predicting residual stress profiles.

Phase transformation due to severe thermo-mechanical conditions of the machining process is a key study of machining modeling. Complex phenomena such as subsurface layer modifications (Umbrello et al. 2010), dynamic recrystallizations, and phase transformations are of particular interest to researchers.

The surface quality of machined components is largely determined by their surface topography and roughness. Analytical modeling is one of the areas where promising results have been obtained. The prediction of surface roughness for different processes, such as turning and milling including vibrations, has obtained good results compared to empirical tests (Jawahir et al. 2011).

**Microstructure** Many studies have focused on the influence of the microstructure in the bulk material on the machining outputs. Heterogeneous modeling, where the microstructure in the material is physically modeled, is able to determine cutting forces with better agreement than homogeneous models (Abouridouane et al. 2012) in chip morphology and surface defects.

Advanced studies where the modeled microstructure reflects the internal dislocations, sliding planes of the phases, and grain boundary effect are considered key research areas (Zhang et al. 2012).

**Burr Formation** In recent years, predicting and understanding burr formation has received much attention. Finite-element models is employed for simulation of burr formation for operations ranging from drilling and milling to turning (Leopold and Wohlgemuth 2009).

**Tool Life/Tool Wear** Tool-wear affects workpiece quality significantly. Consequently, tool-wear prediction and tool substitution policy are very important for minimizing the machining costs and optimizing performance. By characterizing the tool-workpiece contact pair and using wear rate phenomenological models as a base, researchers have developed new wear rate models combining inverse analysis and finite element method. Updating the tool geometry by nodal movements, the impact of the wear in the tools, can be shown (Klocke and Frank 2006).

**Machining Stability** Vibrations and chatter are two of the major problems experienced in the machining industry. The cutting forces excite the structural dynamics and lead to relative vibrations between the cutting edge and workpiece. Machining vibrations are classified as either forced vibrations or chatter and may have a negative impact on the tolerance and surface quality of the workpiece. Machining stability through the use of mechanistic models is one of the areas where relevant advances have been carried out during recent years, predicting process windows to increase productivity (Altintas and Weck 2004).

**Part Distortion** One of the major requirements in machining processes is the prediction of component distortions that occur largely due to bulk and surface residual stresses. The main goal is to predict distortions occurring during multi-operation machining of industrial components (Urresti et al. 2009) in order to define a suitable machining strategy and cutting parameters.

## Future Needs on Modeling

The following are considered the future needs for modeling enhancement:

- Further development of physics-based models is strongly recommended to assist understanding of machining processes. Such models, however, imply considerable computational costs, and thus multi-scale modeling is needed to capture process physics.
- Significant progress has been made in predicting fundamental variables, but progress in

model development has been limited. Models of industry-relevant outcomes such as residual stresses, tool wear, component distortions, etc. need to be developed.

- A move from 2D to 3D model development is needed which again will imply considerable computational costs. The use of hybrid modeling could solve this problem.
- Reliable data for material and tool–chip contact behavior (i.e., more realistic material and contact laws and advanced parameter identification) is required to solve issues such as machinability.
- There is a need for "calibration" in all case studies in order to obtain accurate quantitative predictions. However, modeling is robust enough for predicting trends.
- It is strongly recommended that future modeling studies identify and provide information about the expected uncertainty in results.
- Process Chain Modeling is required in order to include prior manufacturing processes effects. For instance, more information about bulk residual stresses in forming will help establish a greater degree of accuracy in machining.
- New numerical methods such as meshless techniques, which prevent problems with severe mesh distortions, should be taken into account as an alternative modeling option.
- Innovative cutting tools, including advanced coatings, tool grades, and complex geometry, and cutting fluid effects should be considered in future modeling efforts.

## Cross-References

▶ Broaching
▶ Chatter Prediction
▶ Chip-Forms, Chip Breakability, and Chip Control
▶ Computer-Aided Process Planning
▶ Computer-Integrated Manufacturing
▶ Cutting Temperature
▶ Cutting, Fundamentals
▶ Drilling
▶ Flow Stress, Flow Curve
▶ Gear Cutting
▶ Grinding
▶ Grinding Monitoring
▶ Machinability
▶ Modeling of Face Milling
▶ Molecular Dynamics for Cutting Processes
▶ Simulation of Manufacturing Systems

## References

Abouridouane M, Klocke F, Lung D, Adams O (2012) A new 3D multiphase FE model for micro cutting Ferritic–Pearlitic carbon steels. CIRP Ann Manuf Technol 61(1):71–74

Altintas Y, Weck M (2004) Chatter stability in metal cutting and grinding. CIRP Ann Manuf Technol 53(2):619–642, Key Note Paper of STC-M

Arrazola P-J, Özel T, Umbrello D, Davies M, Jawahir IS (2013) Recent advances in modelling of metal machining processes. CIRP Ann Manuf Technol 62:695–718

Fang N, Jawahir IS, Oxley PLB (2001) A universal slip-line model with non-unique solutions for machining with curled chip formation and a restricted contact tool. Int J Mech Sci 43:557–580

Jawahir IS, Brinksmeier E, M'Saoubi R, Aspinwall DK, Outeiro JC, Meyer D, Umbrello D, Jayal AD (2011) Surface integrity in material removal processes: recent advances. CIRP Ann Manuf Technol 60(2):603–626

Klocke F, Frank P (2006) Simulation of tool wear in hard turning. In: Proceding of the 9th CIRP international workshop on modelling of machining operations, Bled, 11–12 May 2006, pp 499–506

Leopold J, Wohlgemuth R (2009) Modelling and simulation of burr formation: state-of-the-art and future trends. In: Conference on burrs, analysis, control and removal, Kaiserslautern (Germany): University of Kaiserslautern

Özel T, Davim P (2009) Intelligent machining. Wiley, London. ISBN 9781848211292

Sima M, Ozel T (2010) Modified material constitutive models for serrated chip formation simulations and experimental validation in machining of titanium alloy Ti–6Al–4V. Int J Mach Tool Manuf 50:943–960

Umbrello D, Outeiro JC, M'Saoubi R, Jayal AD, Jawahir IS (2010) A numerical model incorporating the microstructure alteration for predicting residual stresses in hard machining of AISI 52100 steel. CIRP Ann Manuf Technol 59(1):113–116

Urresti I, Nikov S, Brown P, Arrazola PJ (2009) Aerospace gas turbine disc distortion modelling: machining sequence optimization. In: 12th CIRP conference on modelling machining operations, San Sebastian

Valiorgue F, Rech J, Hamdi H, Gilles P, Bergheau JM (2012) 3D modelling of residual stresses induced in finish turning of an AISI 304L stainless steel. Int J Mach Tool Manuf 53:77–90

Wang X, Jawahir IS (2007) Recent advances in plasticity applications in metal machining: slip-line models for machining with rounded cutting edge restricted contact grooved tools. Int J Mach Mach Mater 2:347–360

Zhang Y, Mabrouki T, Nelias D, Courbon C, Rech J, Gong Y (2012) Cutting simulation capabilities based on crystal plasticity theory and discrete cohesive elements. J Mater Process Technol 212(4):936–953

# Modeling of Face Milling

Volker Schulze
Institute of Production Science (wbk), Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany
Institute for Applied Materials (IAM-WK), Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany

## Synonyms

Modeling of face milling operations; Modeling of face milling processes

## Definition

Face milling is the machining process with highest productivity to effectively machine large surfaces of metallic components. Thus it is of utmost interest to optimize this widely applied process.

One important possibility to examine, analyze, and improve machining processes is the modeling and simulation. Using this technique the performance of cutting processes and characteristics of manufactured components can be predicted and planned in order to optimize productivity, quality, and cost (Tapoglou and Antoniadis 2012; van Luttervelt et al. 1998).

Modeling of face milling includes all modeling approaches dealing with the cutting process face milling. There are models describing the kinematics of the process itself; but in most cases one of the listed targets is being examined:

- Force system/cutting forces
- Cutting temperatures
- Workpiece temperatures
- Chip geometry and chipping volume
- Surface characteristics (especially roughness)
- Tool wear

To reach these goals, different approaches exist which are listed as follows:

- Empirical models
- Analytical models
- Numerical models
- Neural networks
- Regression models

## Theory and Application

### Modeling Approaches for Face Milling Operations

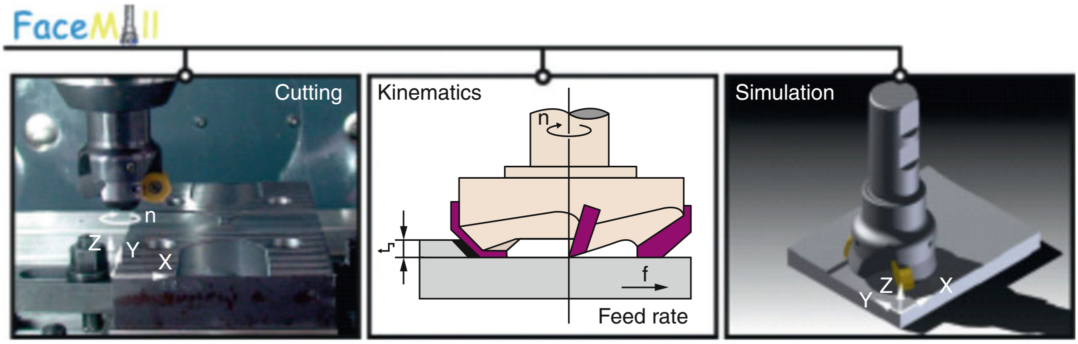
For the modeling of face milling, different methods and modeling techniques such as numerical, analytical, and empirical approaches have been developed and examined. This chapter gives an overview of the state of the art concerning modeling of face milling. Due to the diversity of the existing models, they are classified into four categories:

- Modeling process kinematics and machine tool
- Modeling chip formation in face milling processes
- Modeling face milling with focus on the tool
- Modeling face milling with focus on the workpiece

### Modeling Process Kinematics and Machine Tool

For milling in general, there are numerous works dealing with the modeling of process kinematics (Altintas and Engin 2001; Altintas and Merdol 2007; Altintas and Jin 2011; Surmann and Enk 2007; Surmann and Biermann 2008; Surmann and Krebs 2012; Becke 2011; Schulze and Becke 2011; Schulze et al. 2012; Budak et al. 2009; van Luttervelt et al. 1998; Rüeg and Gygax 1992).

Regarding face milling their number decreases significantly. Tapoglou developed a kinematic model of the face milling process which has




**Modeling of Face Milling, Fig. 1** Face milling experiment (*left*), sketch of kinematics (*middle*), and 3D simulation (*right*). (Tapoglou and Antoniadis 2012)

been embedded in a commercial 3D CAD environment (Fig. 1).

Considering the original tool geometry, the model is able to calculate the undeformed chip geometry, the geometry and surface roughness of the machined workpiece, and the cutting forces. The simulations were verified by experiments and showed good agreement (Tapoglou and Antoniadis 2012). In 2001 Altintas already modeled the geometry of milling tools using helical flutes wrapped around a parametric body of a milling tool. Using local coordinate systems, he orientated the edge geometry of the cutting inserts within the global coordinate system of the milling tool (Fig. 2).

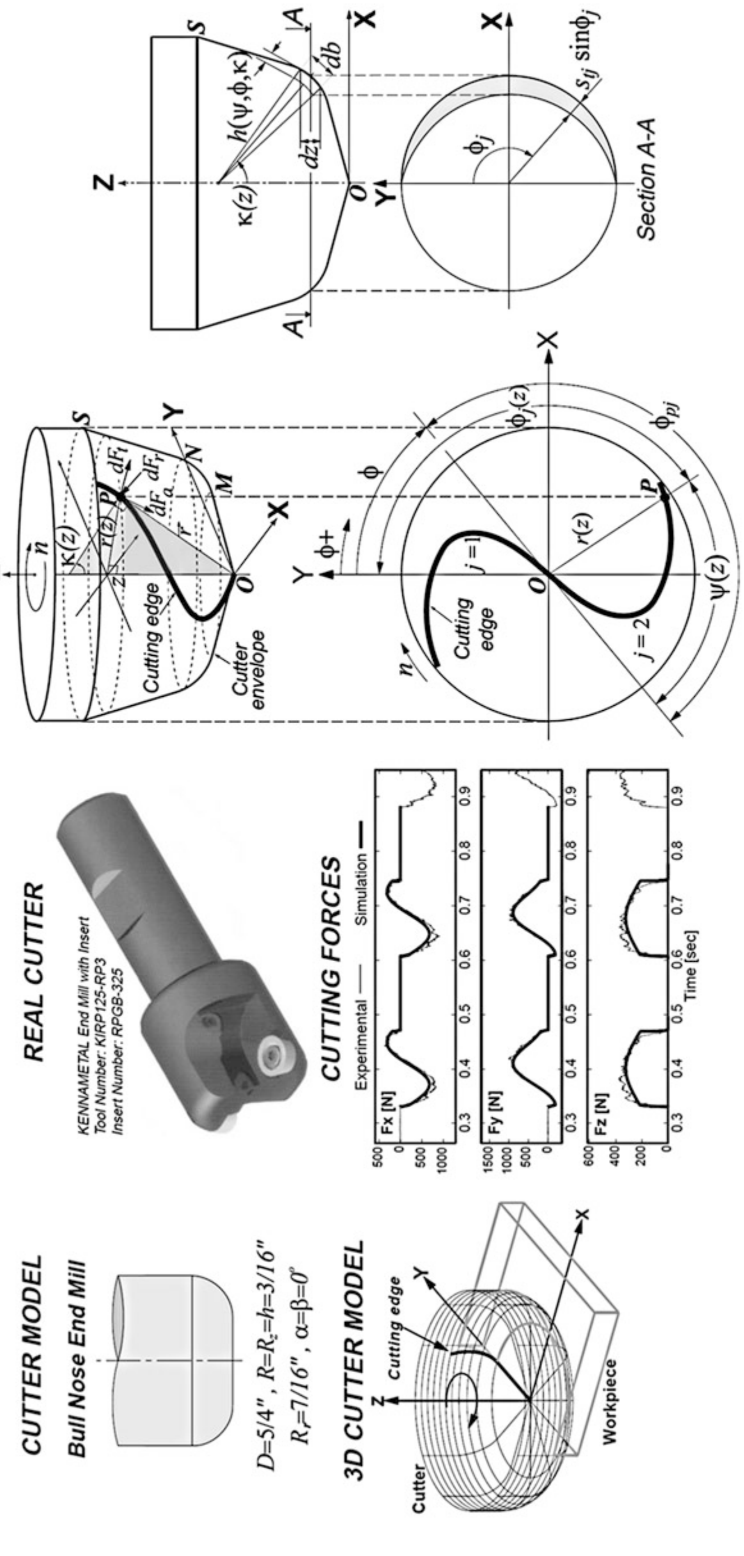
With the model the chip thickness can be calculated at each point using the true kinematics of the process considering structural vibrations of tool and workpiece. This general model is able to predict the cutting forces, vibrations, the dimensional surface finish, and chatter marks. The model has been implemented in a software tool for process planning (Altintas and Engin 2001). Zheng developed a model representing the milling process as simultaneous actions of a number of single-point cutting tools (Zheng et al. 1999). The model predicts the cutting forces in face milling for different milling tools, tooth geometries, material properties, and process parameters. Ruzhong also derived a model for a cutting tool with multiple cutting inserts by superposition of single-tooth profiles predicting the pulsation of the cutting force at face milling (Ruzhong and Wang 1983). Kim developed a model representing multi-tooth oblique cutting in a three-directional reference system using a system with 6 degrees of freedom and a zero-order cutting process system in a closed-loop configuration (Fig. 3).

The model calculated the dynamic forces of the face milling process based in the regenerative vibration theory. The results are in better agreement with experimental results than the calculated static cutting forces (Kim and Ehmann 1993).

## Modeling Chip Formation in Face Milling Processes

The process of chip formation is decisive for all cutting processes, as it describes the characteristics of the process including influences of material, tool, and cutting parameters. Predicting the chip formation provides an increase of knowledge and understanding of the face milling process and thus enables optimization and improvement of the entire process. The modeling of chip formation at face milling is not very common and often modeled using 2D approaches not really representing the face milling process (Sadeghinia et al. 2007). Tapoglou calculated the undeformed chip thickness modeling the kinematics of the face milling process (Tapoglou and Antoniadis 2012) (Fig. 4).

Pittallà simulated the 3D-chip formation of face milling using DEFORM 3D. The material model has been calibrated using the analytical model OXCUT, developed by Oxley (Pitallà and Monno 2010) (Fig. 5).




**Modeling of Face Milling, Fig. 2** Models of milling tools. (Altintas and Engin 2001)

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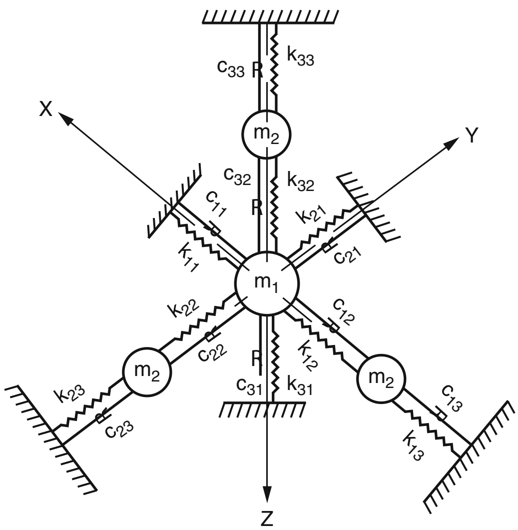
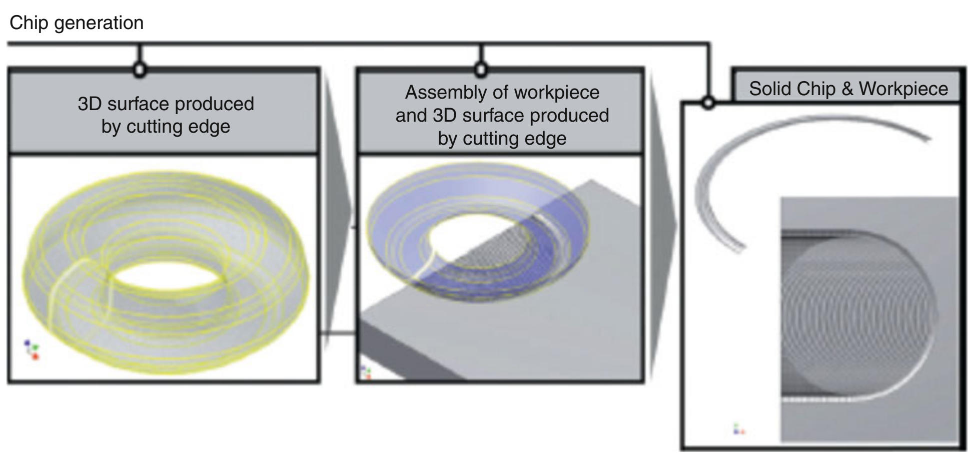
## Modeling of Face Milling with Focus on the Tool

Most works regarding modeling of the face milling process deal with the prediction of the resulting cutting forces and the tool wear (Altintas and Engin 2001; Pandey and Shan 1972; Bayoumi et al. 1994a, b; Fu et al. 1984; Adolfsson and Ståhl 1995; Gu et al. 1997; Kim et al. 1999; Chang 2005; Hwang et al. 2003; Saglam 2011; Kuljanic and Sortino 2005; Baro et al. 2005; Aykut et al. 2007; Bhattacharyyaa et al. 2007; Patel and Joshi 2005; Guzeev and Pimenov 2011; Bajic et al. 2012; Armarego et al. 1995).

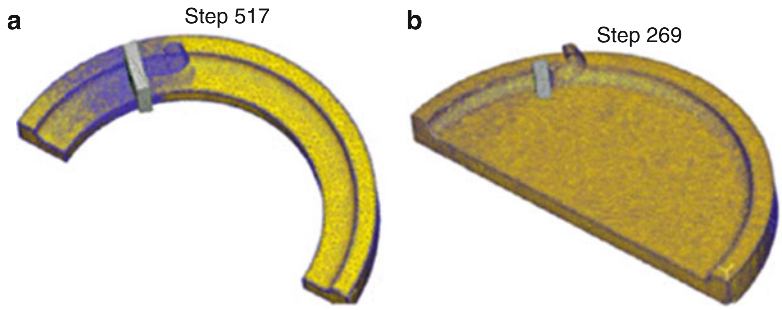



**Modeling of Face Milling, Fig. 3** Vibratory model of the dynamic cutting process. (Kim and Ehmann 1993)

Pandey developed an analytical model based on a shear plane model calculating the forces at each tooth of a face milling tool. The modeled forces showed good agreement with experimental results (Pandey and Shan 1972). Fu developed a mechanistic model to predict the force system of the face milling of 390 casting aluminum in relation to cutting parameters and tool geometry (Fu et al. 1984). Using his kinematic model, Kim was able to predict the dynamic forces of the face milling process matching very well with experimental results (Kim and Ehmann 1993). Bayoumi developed an analytical mechanistic approach to model cutting forces and resulting cutting energy, torque, and power of the face milling process (Bayoumi et al. 1994a, b). Based on Oxley's work, Young showed the use of the orthogonal cutting theory to predict the cutting forces in face milling in relation to the workpiece material and the cutting parameters (Oxley 1989; Young et al. 1993). Altintas used his kinematic model to predict the cutting forces during face milling with good agreement to experimental data (Altintas and Engin 2001). Hwang used the drop of the cutting force at the end of the immersion angle to calculate the resulting force at an




**Modeling of Face Milling, Fig. 4** Modeled geometry of cutting tool and workpiece and resulting chip and workpiece surface. (Tapoglou and Antoniadis 2012)




**Modeling of Face Milling, Fig. 5** Chip formation in simulation with (**a**) and without (**b**) edge radius of 0.05 mm. (Pitallà and Monno 2010)

insert in feed and cross-feed direction using an analytical model (Hwang et al. 2003). Also models based on neural networks are used to determine the cutting forces to establish a condition monitoring in face milling (Saglam 2011; Aykut et al. 2007). Kuljanic developed a method called TWEM (tool wear estimation method) to detect tool wear in face milling which is based on measured cutting force signals (Kuljanic and Sortino 2005). He defined cutting force indicators describing the relations between cutting forces and tool wear. Bhattacharyya also modeled the tool wear in face milling processes using the real-time signal of the machining process. He called his model "online tool condition monitoring" (OLTCM) which is based on multiple regression models which are combined to the final tool (Bhattacharyyaa et al. 2007).

## Modeling of Face Milling with Focus on the Workpiece

As all machining processes, face milling leads to thermal and mechanical loadings of the machined workpieces. As a result residual stresses, distortion, phase transformations, and modifications of the topography of the workpiece's surface occur (Altintas and Budak 1995).

Investigating the thermal load of machining processes regarding the heat input into the workpiece, Fleischer showed that it is possible to model specific effects of the machining process by means of mathematical functions considering the cutting speed, feed rate, and tool diameter (Fleischer et al. 2007). Based on these results, Pabst developed a mathematical model for the face milling process to describe the heat input into workpieces at dry machining. The mathematical function is based on a power law approach and was determined by a regression analysis of experimental investigations. The considered parameters were the cutting speed, feed rate, cutting depth, cutting width, cutting angle, and the radius of the cutting edge as well as the influence of upcut milling and downcut milling (Pabst et al. 2010):

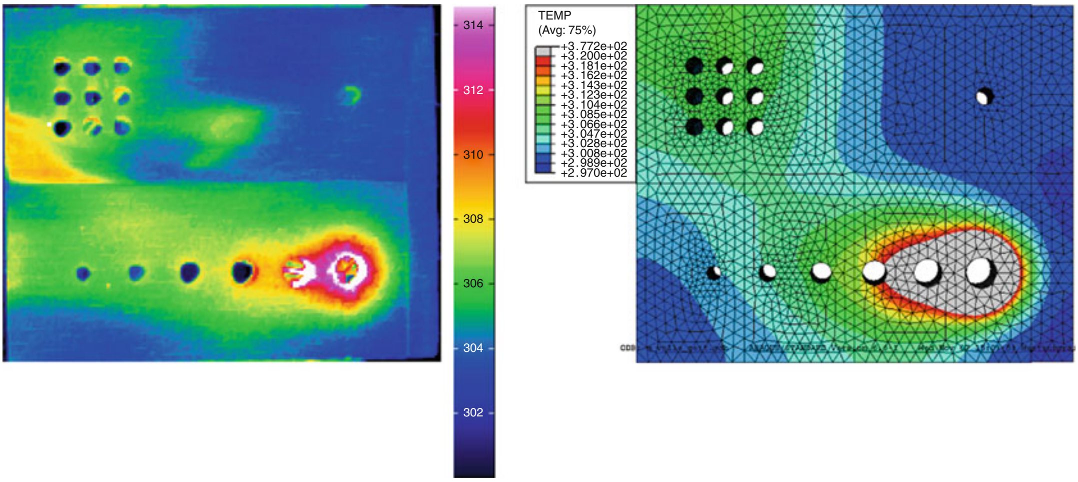
$$\dot{q}\left(f_z, v_c, a_p, r_\varepsilon, \gamma, a_e\right) = \left(14,480 \cdot f_z^{-0.68} \cdot v_c^{0.76} \cdot a_p^{0.21} \cdot a_e^{-0.31} \cdot r_\varepsilon^{0.19} \cdot \gamma^{-0.14}\right) \cdot [1.09 \quad (\text{for downcut milling})]$$



The model was verified by experiments and provides input data for a FEM simulation of workpiece distortion caused by the heat input in face milling processes (Schulze et al. 2008, 2009a, b, c; Pabst et al. 2010; Pabst 2008) (Fig. 6). The investigations of Denkena et al. are used to describe and understand height deviation, transition deviation, and surface roughness as main influences of the surface quality in parallel machining (Denkena et al. 2013). The experimental results and modeling approaches show that the characteristic shape deviations can be predicted.

Ng used Abaqus/Explicit to simulate an orthogonal cutting process to model high-speed face milling. He developed two FE models to assist in explaining the effects of tool wear on the temperature and shear stress distribution in the workpiece material. The FE results correspond to experimental observations (Ng et al. 2004).

Benardos investigated the modeling of surface roughness for face milling in his research. He determined significant factors with the aid of Taguchi's DOE and presented a neural network




**Modeling of Face Milling, Fig. 6** Comparison of measured (*left*) and calculated workpiece temperatures. (Pabst 2008)

approach (NNA) based on the DOE results to predict the surface roughness for any new combination of values for the most important factors. The influence of back cutting on the surface finish obtained by face milling operations was investigated by (Franco 2008). He modeled the final part surface from tool runouts and height deviations with a numerical approach. The surface profiles predicted by the model showed good agreements with the experimental observations (Benardos and Vosniakos 2002). Bajic used regression models and neural networks to model the influence of cutting parameters on the surface roughness in face milling processes (Bajic et al. 2012). Felhö modeled different insert shapes (square, octagonal, circular, and dodecagonal) for cutting tools. The modeling strategy allows to model equal and different insert shapes in the cutting tool (Felhö et al. 2015). The based calculation method for the surface roughness was first developed for turning (Arrazola et al. 2013) experiments and has further input from a model developed for face milling (Peters et al. 2001).

## Cross-References

- ▶ Chip-Forms, Chip Breakability, and Chip Control
- ▶ Cutting, Fundamentals

## References

Adolfsson C, Ståhl J-E (1995) Cutting force model for multi-toothed cutting processes and force measuring equipment for face milling. Int J Mach Tools Manuf 35(12):1715–1728

Altintas Y, Budak E (1995) Analytical prediction of stability lobes in milling. Ann CIRP 44(1):357–362

Altintas Y, Engin S (2001) Generalized modeling of mechanics and dynamics of milling cutters. CIRP Ann Manuf Technol 50(1):25–30

Altintas Y, Jin X (2011) Mechanics of micro-milling with round edge tools. CIRP Ann Manuf Technol 60(1):77–80

Altintas Y, Merdol SD (2007) Virtual high performance milling. CIRP Ann Manuf Technol 56(1):81–84

Armarego EJA, Wang J, Deshpande NP (1995) Computer-aided predictive cutting model for forces in face milling allowing for tooth run-out. Ann CIRP 44(1):43–48

Arrazola PJ, Özel T, Umbrello D, Davies M, Jawahir IS (2013) Recent advances in modelling of metal machining processes. Ann CIRP 62(2):695–718

Aykut S, Gölcü M, Semiz S, Ergür HS (2007) Modeling of cutting forces as function of cutting parameters for face milling of satellite 6 using an artificial neural network. J Mater Process Technol 190:199–203

Bajic D, Celent L, Jozic S (2012) Modeling of the influence of cutting parameters on the surface roughness, tool wear and cutting force in face milling in off-line process control. J Mech Eng 58(11):673–682

Baro PK, Joshi SS, Kapoor SG (2005) Modeling of cutting forces in a face-milling operation with self-propelled round insert milling cutter. Int J Mach Tools Manuf 45:831–839

Bayoumi AE, Yücesan G, Hutton DV (1994a) On the closed form mechanistic modeling of milling: specific cutting energy, torque, and power. J Mater Eng Perform 3:151–158

Bayoumi AE, Yucesan G, Kendall LA (1994b) An analytic mechanistic cutting force model for milling operations: a theory and methodology. Trans ASME – J Eng Ind 116(3):324–330

Becke C (2011) Prozesskraftrichtungsangepasste Frässtrategien zur schädigungsarmen Bohrungsbearbeitung an faserverstärkten Kunststoffen [Milling strategies with regard to process force directions for low-damage drilling processes of fiber-reinforced plastics], PhD thesis, Karlsruhe Institute of Technology (in German)

Benardos PG, Vosniakos GC (2002) Prediction of surface roughness in CNC face milling using neural networks and Taguchi's design of experiments. Robot Comput Integr Manuf 18:343–354

Bhattacharyyaa P, Senguptaa D, Mukhopadhyayb S (2007) Cutting force-based real-time estimation of tool wear in face milling using a combination of signal processing techniques. Mech Syst Signal Process 21:2665–2683

Budak E, Ozturk E, Tunc LT (2009) Modeling and simulation of 5-axis milling processes. CIRP Ann Manuf Technol 58(1):347–350

Chang C-S (2005) Prediction of cutting forces in milling stainless steels using chamfered main cutting edge tool. J Mech 21(3):145–155

Denkena B, Köhler J, Hasselberg E (2013) Modeling of workpiece shape deviations in face milling of parallel workpiece compounds. Procedia CIRP 8:176–181

Felhö C, Karpuschewski B, Kundrák J (2015) Surface roughness modelling in face milling. Procedia CIRP 31:136–141

Fleischer J, Pabst R, Kelemen S (2007) Heat flow simulation for dry machining of power train castings. Ann CIRP 56(1):117–122

Franco P (2008) Effect of cutter axis tilt and average feed deviations on surface roughness of milled parts. In: International multi-conference on engineering and technological innovation: IMETI, Orlando

Fu HJ, Devor RE, Kapoor SG (1984) A mechanistic model for the prediction of the force system in face milling operations. J Eng Ind 1(2):81–88

Gu F, Kapoor SG, Devor RE, Bandyopadhyay P (1997) An enhanced cutting force model for face milling with variable cutter feed motion and complex workpiece geometry. J Manuf Sci Eng 119(4):467–475

Guzeev VI, Pimenov DY (2011) Cutting force in face milling with tool wear. Russ Eng Res 31(10):989–993

Hwang JH, Oh YT, Kwon WT (2003) In-process estimation of radial immersion ratio in face milling using cutting force. Int J Adv Manuf Technol 22:313–320

Kim HS, Ehmann KF (1993) A cutting force model for face milling operations. Int J Mach Tools Manuf 33(5): 651–673

Kim T-Y, Woo J, Shin D, Kim J (1999) Indirect cutting force measurement in multi-axis simultaneous NC milling processes. Int J Mach Tools Manuf 39:1717–1731

Kuljanic E, Sortino E (2005) TWEM, a method based on cutting forces – monitoring tool wear in face milling. Int J Mach Tools Manuf 45:29–34

Ng E-G, Szablewski D, Dumitrescu M, Elbestawi MA, Sokolowski JH (2004) High speed face milling of an aluminium silicon alloy casting. CIRP Ann Manuf Technol 53(1):69–72

Oxley PLB (1989) Mechanics of machining: an analytical approach to assessing machinability. Ellis Horwood, Chichester

Pabst R (2008) Mathematische Modellierung der Wärmestromdichte zur Simulation des thermischen Bauteilverhaltens bei der Trockenbearbeitung, [Mathematical modeling of the surface heat flux to simulate the thermal behavior of workpieces in dry machining], PhD thesis, University Karlsruhe (TH) (in German)

Pabst R, Fleischer J, Michna J (2010) Modelling of the heat input for face-milling processes. Ann CIRP 59(1): 121–124

Pandey C, Shan HS (1972) Analysis of cutting forces in peripheral and face milling operations. Int J Prod Res 10(4):370–391

Patel KM, Joshi SS (2005) Mechanics of machining of face-milling operation performed using a self-propelled round insert milling cutter. J Mater Process Technol 171:68–76

Peters J et al (2001) Contribution of CIRP to the development of metrology and surface quality evaluation during the last fifty years. Ann CIRP 50(2):471–488

Pitallà GM, Monno M (2010) 3D finite element modeling of face milling of continuous chip material. Int J Adv Manuf Technol 47:543–555

Rüeg A, Gygax P (1992) A generalized kinematics model for three- to five-axis milling machines and their implementation in a CNC. CIRP Ann Manuf Technol 41(1): 547–550

Ruzhong Z, Wang KK (1983) Modelling of cutting force pulsation in face-milling. Ann ClRP 32(1):21–26

Sadeghinia H, Razfar MR, Takabi J (2007) 2D finite element modeling of face milling with damage effects. In: 3rd WSEAS international conference on applied and theoretical mechanics, Spain, pp 145–150

Saglam H (2011) Tool wear monitoring in bandsawing using neural networks and Taguchi's design of experiments. Int J Adv Manuf Technol 55:969–982

Schulze V, Becke C (2011) Analysis of machining strategies for fiber reinforced plastics with regard to process force direction. Proc Eng 19:312–317

Schulze V, Pabst R, Michna J (2008) Modelling the heat flux as an input parameter to simulate cutting processes. In Heigel JC, Moylan SP, Ivester RW, Proceedings of the 11th CIRP Conference on Modeling of Machining Operations, pp 155–162, Gaithersburg, MD USA, Sep 16.-18

Schulze V, Pabst R, Michna J (2009a) Modeling of the heat input for the face-milling of EN-GJL-250. In Mondragon Unibertsitateko Zerbitzu Ed., 12th CIRP Conference on Modeling of Machining Operations, Vol 1:243–248, San Sebastian, ES, May 7.-8

Schulze V, Michna J, Pabst R, Hauer Th (2009b) Thermische Belastung beim Stirnplanfräsen [Investigation on the thermal load during end-face milling], In: wt

Werkstattstechnik online, Jahrgang 99, Heft 4, Springer-VDI-Verlag GmbH & Co.KG, pp 281–286 (in German)
Schulze V, Michna J, Pabst R, Hauer T (2009c) Simulation des Wärmeeintrags verbessert Toleranztreue bei der Trockenbearbeitung [Simulation of the heat input for improved tolerance accuracies in dry machining], In: MM Maschinenmarkt, Ausgabe 13, pp 26–28 (in German)
Schulze V, Spomer W, Becke C (2012) A voxel-based kinematic simulation model for force analyses of complex milling operations such as wobble milling. Prod Eng 6(1):1–9
Surmann T, Biermann D (2008) The effect of tool vibrations on the flank surface created by peripheral milling. CIRP Ann Manuf Technol 57(1):375–378
Surmann T, Enk D (2007) Simulation of milling tool vibration trajectories along changing engagement conditions. Int J Mach Tools Manuf 47(9):1442–1448
Surmann T, Krebs E (2012) Optimization of micromilling by adjustment of inclination angles. Procedia CIRP 2:87–91
Tapoglou N, Antoniadis A (2012) 3-Dimensional kinematics simulation of face milling. Measurement 45:1396–1405
van Luttervelt CA, Childs THC, Jawahir IS, Klocke F, Venuvinod PK, Altintas Y, Armarego E, Dornfeld D, Grabec I, Leopold J, Lindstrom B, Lucca D, Shirakashi OT, Sato H (1998) Present situation and future trends in modelling of machining operations progress report of the CIRP working group 'modelling of machining operations'. CIRP Ann Manuf Technol 47(2):587–626
Young H-T, Mathew P, Oxley PLB (1993) Predicting cutting forces in face milling. Int J Mach Tools Manuf 34(6):771–783
Zheng HQ, Li XP, Wong YS, Nee AYC (1999) Theoretical modelling and simulation of cutting forces in face milling with cutter runout. Int J Mach Tools Manuf 39: 2003–2018

## Modeling of Face Milling Operations

▶ Modeling of Face Milling

## Modeling of Face Milling Processes

▶ Modeling of Face Milling

## Modular Design

Mitchell M. Tseng[1,2], Yue Wang[3] and Roger J. Jiao[4]
[1]Feng Chia University, Taichung, Taiwan
[2]The Hong Kong University of Science and Technology, Hong Kong, China
[3]Hang Seng Management College, Hong Kong, China
[4]The George M. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA, USA

### Synonyms

Modularity

### Definition

Modular design refers to designing products by organizing sub-assemblies and components as distinct building blocks (i.e., modules) that can be integrated through configuration to fulfill various customer and engineering requirements.

### Theory and Application

#### Introduction

Modular design is basically to decompose complex systems into simple modules in order to more efficiently organize complex designs and processes. The concept was first introduced by (Starr 1965), in which the use of modular product in production was proposed as a new concept to develop variety. It makes possible to modify specific modules for a new requirement without influencing the main infrastructure, so that the complex problems can be decomposed into several small ones. Modular design concept has been employed in many fields of design and manufacturing.

The main advantages of modular design include design flexibility, augmentation, and cost reduction. Due to grouping the components to each module, the designer can easily modify each module instead of changing the whole design. In addition, the system can be upgraded by adding new functions simply by plugging a new module so that the system can be augmented within a specific range. Furthermore, the modularized components also make possible concurrent engineering and flexible manufacturing. Modular design classified all components in different products into variant and common modules constructed in a core platform. By doing so, it becomes feasible to customize large varieties of high demand products through achieving economy of scale. Current product family design concept and process family approaches are all based on the concept of modular design.

Modular design relies on the product architecture and product platform concepts. Product architecture is defined as a scheme where the physical components are linked to functional elements to form various products (Ulrich and Eppinger 1995). The architecture can be designed as modular, generating a "one-to-one" relationship between functional and physical elements. The purpose is to decouple each element so that a change in one component does not influence changes in others in neither a functional nor a physical way.

The platform is defined as "a set of subsystems and interfaces developed to form a common structure from which a stream of derivative products can be efficiently developed and produced" (Meyer and Lehnerd 1997). Compared to the architecture, the platform concept emphasizes more on the configuration of physical components. The platform is the foundation to build variants of modules to offer product varieties, composed by the common modules shared among the product varieties in a family. The platform is the key to achieve economy of scale, the same as the mass production.

According to current literature, the main challenges of the modular design are to conceive the modular architecture and balance the variants and common modules in the system.

## Modularity and Product Architecture

Product architecture can be defined as the way in which the functional elements of a product are arranged into physical units and the way in which these units interact (Ulrich and Eppinger 1995; Jiao and Tseng 2000). It is quite obvious that all products have some kind of architecture, even if it is not necessarily to have been considered during the design phase (Lanner and Malmqvist 1996). The choice of product architecture has broad implications for product performance, product change, product variety, and manufacturability (Ulrich 1995). Product architecture is also strongly coupled to the firm's development capability, manufacturing specialties, and product strategy (Pimmler and Eppinger 1994).

Typically, product architecture design occurs during the configuration design stage, that is, after conceptual design but before parametric design (Dixon et al. 1988). Configuration design is the process of synthesizing product structures by determining what components and subassemblies are in the product and how they are arranged spatially and logically. Certainly, product configuration controls a product's fabrication and assembly characteristics. It also controls a product's adaptability necessary to respond to changes in customer requirements.

Often, a product's architecture is thought of in terms of its modules (Ulrich and Eppinger 1995). A module is a physical or conceptual grouping of components. Modularity is the concept of decomposing a system into independent parts or modules that can be treated as logical units (Pimmler and Eppinger 1994). Modularity has been defined as the relationship between a product's functional and physical structures such that (1) there is a one-to-one or many-to-one correspondence between the functional and physical structures and (2) unintended interactions between modules are minimized (Ulrich 1994, 1995; Erens and Verhulst 1997).

There is some related research regarding decomposition and architecture at the system definition stage of product design. The core research begins with Alexander (1964), who describes a design process that decomposes (or partitions) designs into minimally coupled groups. Simon (1981) continues by suggesting that complex design problems can be described in terms of hierarchical structures consisting of "nearly decomposable systems" organized such that the strongest interactions occur within groups and only weaker interactions occur among (between) groups. Pahl and Beitz (1996) and Suh (1990) build upon these concepts by modeling the functional requirements of product design in terms of exchanges of energy, materials, and signals between functional elements organized in hierarchical functional structures. Pimmler and Eppinger (1994) extend Steward's design structure matrix (DSM) model (1981) to investigate the interaction issues and give considerable insight into product architecture and decomposition. While interactions embody the technical aspects of product architecture (Lanner and Malmqvist 1996), the economic aspects of product architecture design are dealt with by Erixon et al. (1996) through a method called modular function deployment (MFD). Ulrich (1995) defines several types of product architectures in terms of how the functional elements are mapped onto physical components and relates the strategic importance of architecture choice to firm performance. Henderson and Clark (1990) also point out the importance of architecture by noting that established firms frequently fail when confronted by a novel architecture. Ulrich and Eppinger (1995) provide a methodology for developing product architecture, although interactions are only considered after the architecture is chosen (Pimmler and Eppinger 1994).

## Modular Design

The application of architecture and modularity to design results in modular product design so as to accommodate agile product development (Anderson 1997). Modular product design refers to designing products, assemblies, and components that fulfill various functions through the combination (configuration) of distinct building blocks (modules) (Pahl and Beitz 1996; Kusiak and Huang 1996). From a study of seven companies, Erlandsson et al. (1992) have shown that increased modularity of a product gives positive effects in the total flow of information and material in a company, from development and purchasing to storage and delivery.

Issues associated with modular design include (1) module creation/identification, (2) interface analysis/evaluation, and (3) module selection/configuration, viz., synthesis. Pahl and Beitz (1996) stress the importance of functional structures in modular product development by classifying modular function space into basic, auxiliary, adaptive, special, and customer-specified functions. Karmarkar and Kubat (1987) discuss the module selection problem from an operations research perspective. Kusiak and Huang (1996) present a graphical representation of product modularity and propose a heuristic approach to module identification. Kohlhas and Birkhofer (1996) develop a program system for the computer-aided development of structures for modular systems. Their system focuses on the aspect of modular configuration. Erixon (1996) systematizes procedures for modular product design mainly concerning a matrix of modular function deployment (MFD) and design for manufacturability and assembly (DFMA) analysis. The MFD focuses mainly on the evaluation of module integration. Hillström (1994) proposes a method that helps the designer clarify how interfaces between modules influence module functions and to select the best interface location. His method is based on axiomatic design theory (Suh 1990) and contributes mostly to mechanical part design.

In summary, current practice refers to modules mostly as physical parts or components in the context of manufacturing and assembly that lie in the process domain. Efforts are rarely put on the functional and/or physical domains of design, especially in terms of systematic planning of modularity starting from early conceptual design stages.

In addition, current research investigates the architecture and modular product design mostly in the context of a single product. Since manufacturing companies increasingly develop product families to offer a large variety of products with limited development and manufacturing costs, the architecture(s) for product families become more and more important (Meyer 1997). A limited literature has been devoted to addressing issues regarding architecture(s) of product families (Erens and Verhulst 1997; Ishii et al. 1995). Ishii et al. (1994) investigate product family construction through evaluating the costs and value of providing variety whilst the architecture(s) of product families has not been dealt with explicitly. Erens and Verhulst (1997) propose to use various product models to describe the architecture(s) of product families. Essentially, they model the architecture(s) of product families as a packaging of single product models, which fails to capture underlying characteristics of product family architecture as different from architectures of individual products.

Fujita and Ishii (1997) point out one important characteristic to discern the architecture of a family of products from that of a single product, i.e., the simultaneous handling of multiple products. The implications of this simultaneity of multiple product variants help us understand and capture the difference between these two types of architectures. While the architecture of a single product is mostly concerned with modularity, this research contends that the product family architecture involves two characteristics of design: (1) the modularity of a product structure, and (2) the commonality among product variants. This will be elaborated in Modularity and Commonality, together with class-member relationships.

A typical four step process to establish modular architecture is proposed in (Ulrich and Eppinger 2000):

1. Develop a conceptual model of components and functions for a product;
2. Cluster the elements, regroup components inside of modules in the model according to:
   (a) Assembly precision: two components are in the same module when a precise assembly is required in order to reduce the number of precise operations;
   (b) Function sharing: when sharing the same components, two functional elements could be designed inside a single module;
   (c) Technological simplicity: design module with the considerations in technological simplicity and production advantages;
   (d) Localization of change: isolate the component in a module if it has a high possibility of change;
   (e) Accommodating variety: isolate the components that are various within a product family;
   (f) Enabling standardization: standardize a module if the product family share the same components;
   (g) Portability interfaces: group components sharing the same flux type
3. Create a geometric layout to better detecting interfaces and modules;
4. Identify important interactions in the conceptual model to find modules and the persons in charge of modules.

## Multiple Views of Modular Design

During product development, many different product descriptions can be recognized for different business functions and in different phases of development. The descriptions are represented by product models that act as a backbone for combined product information (Krause et al. 1993). The product modeling framework is constituted by the chromosome model (Andreasen, in his unpublished note of WDK workshop in 1992), which is based on the theory of technical systems (Hubka and Eder 1988), complemented with "genetic" information that captures the origin of the design characteristics (hence "chromosome").

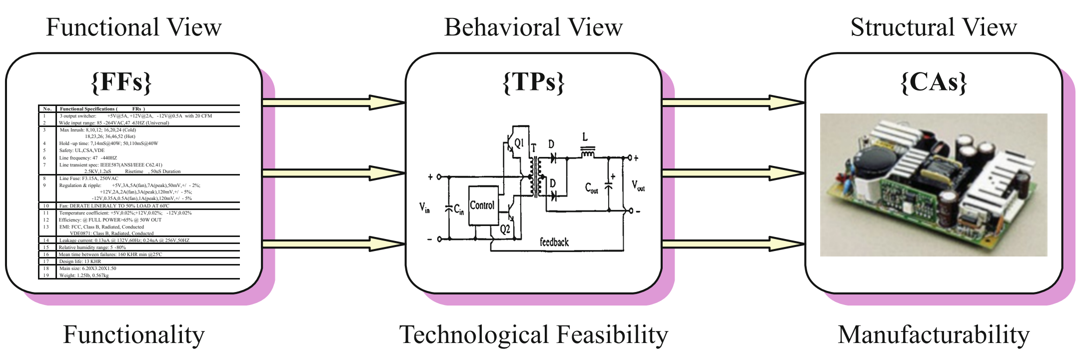
In the theory of technical systems, it is stated that four different types of models are needed to describe a technical system and the transformation process that it affects. These are termed as the process, function, organ and component structures, and are said to define the design characteristics of the transformation system. In a design process context, it is also necessary to have a model that states the goals for the design process, i.e., the design specification. The specification and the structures are linked by causal relations: the process determines the functions, the functions are created by the organs, and the organs are materialized by the components.

Design process models describe the process of establishing the design characteristics of a design object. Figure 1 illustrates one variant of the "overall" design process model as indicated (Andreasen, in his unpublished note of WDK workshop in 1992). Similar models are included in most textbooks on mechanical design (see, for example, Hubka and Eder 1988; Pahl and Beitz 1996). According to these authors, the design process can be described as a process in which an abstract problem formulation in terms of a "need", is successively transformed into a manufacturable product description. The process can be divided into a number of major phases in which particular characteristics of the system are established. These phases can be divided into smaller steps where sub-problems are addressed, typically using the general problem-solving approach summarized by Suh (1990). The general problem-solving process includes a problem statement in terms of requirements and objectives, the search for alternative solutions, and the selection of the "best" solution; it leads to decisions that influence subsequent processes. It is only at this level that there is some empirical evidence that this is a reasoning pattern followed by practicing designers. These patterns are effectively described by the theory of domains. This theory describes the design process in a more flexible way by suggesting that the product chromosome (the set of design characteristics) should be seen as a basic map, on which the process of the design process is charted.

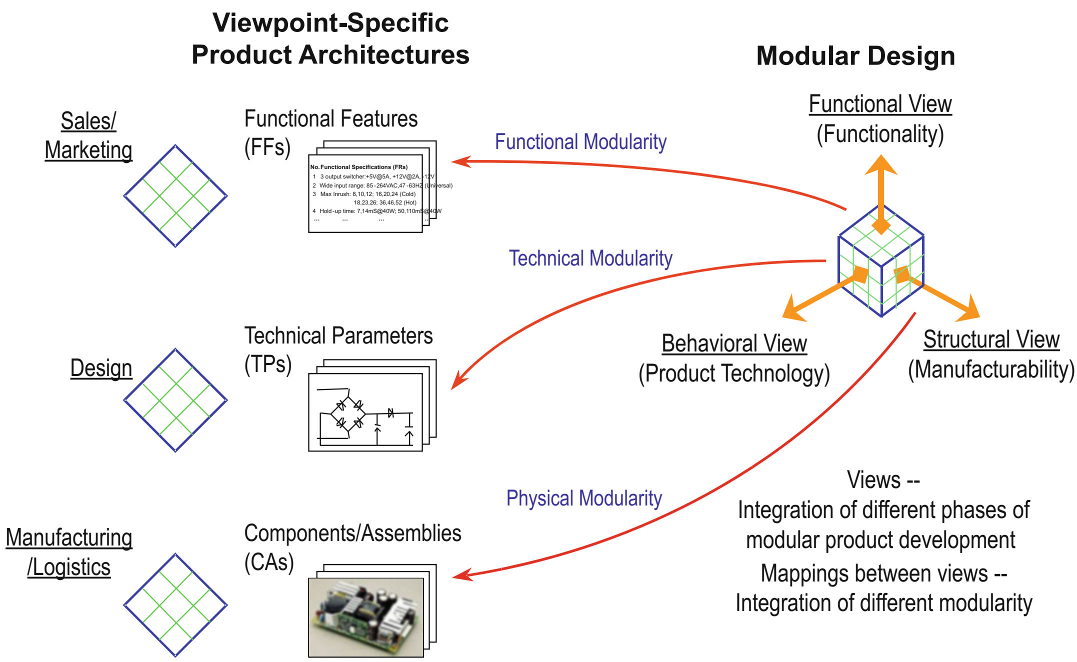
Consistent with the chromosome model proposed by Andreasen and design domains (Suh 1990), modular design should entail a FBS-view product model that evolves through cascading design mappings. Figure 2 shows a FBS view based representation of the modular design process. As illustrated in Fig. 2, a product structure consists of three distinctive views, viz., the functional, behavioral and structural (noted as FBS) views. These three views are characterized by functional features (FFs), technical parameters (TPs), and component/assemblies (CAs), respectively. Each particular view captures a specific aspect of product information, involving functionality (functional structures), technological feasibility (technological solutions/product technologies), or manufacturability (physical structures). The transformation of a technical system (Hubka and Eder 1988), i.e., the design process, is instantiated by mappings between views that embody the cooperation efforts between different phases of product development.

## Mapping Between the Views of Modularity

While corresponding to and supporting different phases of product development using a FBS-view product model, modular design integrates




**Modular Design, Fig. 1** Modular design involving a FBS-view product model and cascading design mappings




**Modular Design, Fig. 2** Multiple views of modular design

several business functions in a context-coherent framework. This is embodied by the mappings between the three views of modular design, as shown in Fig. 2. Various types of customer needs (customer groups) are mapped from the functional view to the behavioral view characterized by solution principles (TPs and modular structures). Such a mapping manifests the design activities. The mapping between the behavioral view and the structural view reflects considerations of manufacturing and logistics, where the modular structure and technical modules in terms of TPs are realized by the physical modules in terms of components and assemblies through incorporating assessments of available process capabilities and the economy of scale. The sales and marketing functions involve the mapping between the structural view and the functional view, where the correspondence of a physical structure to its functionality provides necessary information to assist in negotiation among the customers, marketers, and engineers, e.g. facilitating the request-for-quotation decisions.

Table 1 highlights the tasks and methods related to modular product architecture development. In general, it takes place in two layers that deal with different aspects of modular design. First, a variety of product structures are investigated through systematic planning of modularity in three consecutive views, i.e., functional modularity, technical modularity, and physical modularity. Such a modularity analysis yields modules and modular structures in three views. As a whole, the results comprise the architecture for configuration of modular product design. Then in the commonality layer, for each module identified in the first layer, commonality is studied according to various instances of this module (type). Similar instances are clustered to form a group (variant) represented by a base value plus its variation range. The linkage between two layers is manifested through class-member relationships in between. While the objects in the modularity layer are module types (classes), the objects in the commonality layer are instances of specific module types.

**Modular Design, Table 1** Tasks and methods associated with different types of modularity

| | | Modular design | |
|---|---|---|---|
| Issues in product design | Functional view | Behavioral view | Structural view |
| (1) Modularity | Functional modularity | Technical modularity | Physical modularity |
| Modules | Functional modules | Technical modules | Physical modules |
| Module variables | $M_{Fi} = \{FFs, Ws\}$ | $M_{Tj} \subset \{TPs\}$ | $M_{Pk} = \{CAs\}$ |
| Interaction measure | FFs relevance | Design coupling | Physical interaction |
| Modular structure | N/A | Topological structure (solution principle) | Configuration structure (bill-of-material) |
| Module identification (decomposition) | Pareto analysis qualitative classification | Design matrix decomposition (DMD) | Interaction matrix analysis (IMA) |
| | | | Modular function deployment (MFD) |
| Concerns | Customer segmentation | Technological feasibility | Manufacturability |

## Modularity and Commonality

Modularity and commonality are the key issues in the modular design. Modularity is decomposition of product structures and applicable to describing product type, and commonality resembles the grouping of similar product variants of a specific product type characterized by modularity (Jiao et al. 2007a, b). Modularity of low granularity can increase the absolute number of repetitions to reduce assembly cost and other related cost, but it may defeat the purpose of modularity. The use of too many common modules across different products may degrade potential product performance, because the common components may not be optimal for the product. Therefore, there is a balancing point of granularity. Either too fine, such as molecular levels, or too rough, such as subsystems level, is not productive in perspective of mass customization and the product variety. Designers should balance the commonality with distinctiveness of each product in the family (Simpson 2004).

Much effort in academic research in the balance of the commonality and modularity has focused on the tradeoff among cost, product performance and market impact. In the tradeoff, commonality index usually serves as a proxy for the efficiency of a product platform. A commonality index is defined as a metric to evaluate the degree of commonality in a product family, in terms of the number of common components, costs, and manufacturing processes (Thevenot and Simpson 2006). Various types of commonality indices have been proposed in the literature, and almost all of them are considered as a surrogate for estimating manufacturing cost and the foundation to generate product varieties in a product family. For instance, one commonality index, Degree of Commonality Index, proposed in (Collier 1981) can be interpreted as the ratio between the number of common components in a product family and the total number of parts in the family, so that it is very easy to calculate and roughly estimate the manufacturing cost savings. The tradeoff happens when the customer's preference is taken into the consideration. Basically, the essence of proposed approaches is to maximize the commonality of the product family without exceeding customer's preference loss tolerance.

The concepts of modules and modularity are central in constructing an architecture (Ulrich 1995). Table 2 highlights different implications of modularity and commonality underlying modular product architecture development. While a module is a physical or conceptual grouping of components that share some characteristics, modularity tries to separate a system into independent parts or modules that can be treated as logical units (Newcomb et al. 1996). Therefore, decomposition is a major concern in modularity analysis. In addition, to capture and represent product structures across the entire product development process, a product architecture achieves its modularity from multiple viewpoints, including functionality, solution technologies, and physical

**Modular Design, Table 2** Implications of modularity and commonality in a product architecture

| Issues | Modularity | Commonality |
|---|---|---|
| Focused objects | Type (class) | Instances (members) |
| Characteristic of measure | Interaction | Similarity |
| Analysis method | Decomposition | Clustering |
| Product differentiation | Product structure | Product variants |
| Integration/ interaction | Class-member relationship | |

structures. Correspondingly, there are three types of modularity involved in the product architecture, i.e., functional modularity, technical modularity, and physical modularity.

What is important in characterizing modularity is the interaction between modules. Modules are identified in such a way that between-module (inter-module) interactions are minimized whereas within-module (infra-module) interactions may be high (Ulrich 1995). Therefore, three types of modularity in the product architecture are characterized by specific measures of interaction in particular views. As for functional modularity, the interaction is exhibited by the relevance of FFs across different customer groups. Each customer group is characterized by a particular set of FFs. Customer grouping lies only in the functional view and is independent of the other two views, that is, it should be solution-neutral. In the behavioral view, modularity is determined according to technological feasibility of design solutions. The interaction is thus judged by the coupling of TPs to satisfy given FFs regardless of their physical realization in manufacturing. In the structural view, physical interactions derived from manufacturability become the major concern of the physical modularity.

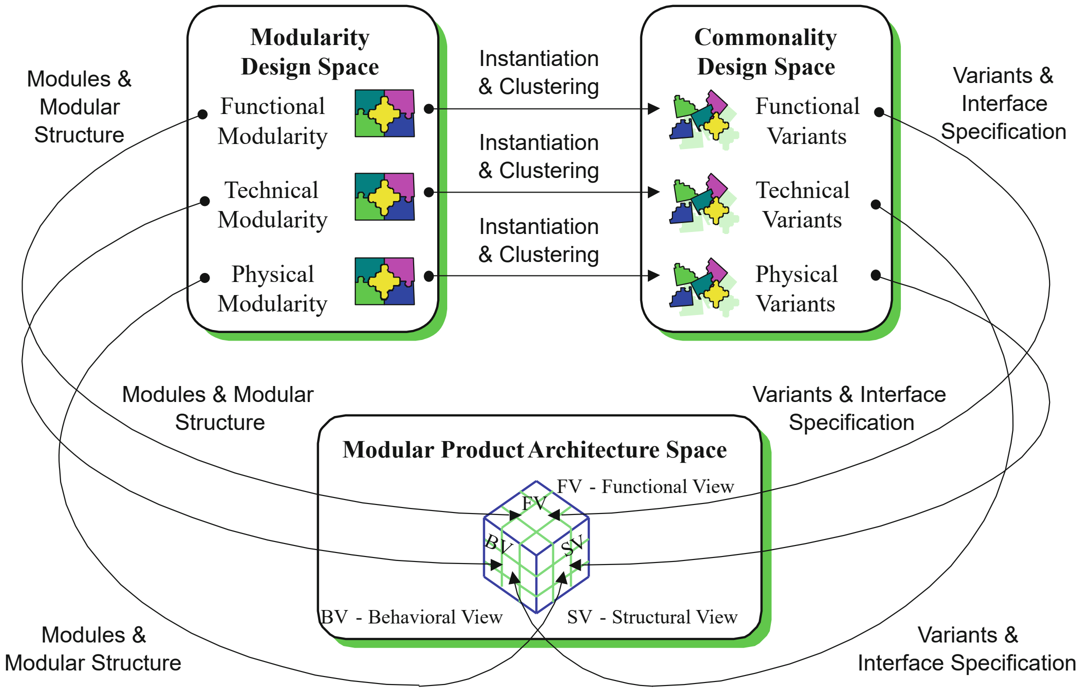
The relation between modularity and commonality is embodied in the class-member relationships. A product structure is defined in terms of its modularity where module types are specified. Product variants derived from this product structure share the same module types and take on different instances of every module type. In other words, a class of products (product family) is described by modularity and product variants differentiate according to the commonality between module instances.

Figure 3 illustrates relations of modularity and commonality in product architecture development. First, the modularity design space is developed. This design space defines viewpoint-specific product modularity, including functional, behavioral, and structural viewpoints. In the commonality design space, diverse instances of specific modules are clustered into chunks. The mappings from the modularity to commonality design spaces are defined by module instantiation and clustering of module instances. In the product architecture design space, fragments of modularity and commonality are incorporated from the respective modularity and commonality design spaces to synthesis into a modular product architecture.

## Applications

Based on modular product architectures, the so-called module-based product family design (Ulrich and Eppinger 1995) has been an important stream of research in product customization. The modular product configuration takes advantage of modular components. The product module involves a one-to-one mapping from a functional requirement to the physical product feature. The product infrastructure with the specified decoupled interfaces between components allows each module to be changed independently. The various modules can be designed independently to satisfy customer's heterogeneous needs.

Modular based design has been applied in many products for mass customization, such as cars, personal computers, and even high rise buildings. The key essence is to leverage on modular design to decouple the modules which the customer can participate in the co-design from others, so that the manufacturing process will not be significantly influenced (Chen et al. 2009). For instance, the customer can configure Dell's computer by defining each module without changing the whole PC infrastructure. Such modular design concept makes mass customization feasible and affordable.




**Modular Design, Fig. 3** Modularity and commonality design spaces and their relations in modular product architecture development

In addition, modular design also influences the flexible manufacturing field. Reconfigurable manufacturing system relies on the various production modules which enables the scalability in response to the market demand and machine adaptability to new product requirements. Due to the flexibility and reconfigurability of the manufacturing system, it can further stimulate product strategies such as mass customization.

## Cross-References

- ▶ Flexible Manufacturing System
- ▶ Mass Customization

## References


Alexander C (1964) Notes on the synthesis of form. Harvard University Press, Cambridge, MA

Anderson DM (1997) Agile product development for mass customization: how to develop and deliver products for mass customization, niche markets, JIT, build-to-order, and flexible manufacturing. Irwin Professional, Chicago

Chen S, Wang Y, Tseng MM (2009) Mass customization as a collaborative engineering effort. Int J Collab Eng 1(1/2):152–167

Collier DA (1981) The measurement and operating benefits of component part commonality. Decis Sci 12(1):85–96. https://doi.org/10.1111/j.1540-5915.1981.tb00063.x

Dixon JR, Duffy MR, Irani R, Meunier K, Orelup M (1988) A proposed taxonomy of mechanical design problems. In: Tipnis VA, Patton EM et al (eds) Proceedings of ASME computers in engineering conference, v(2), American Society of Mechanical Engineers, San Francisco, 31 July – 4 Aug 1988, pp 41–46

Erens F, Verhulst K (1997) Architectures for product families. Comput Ind Spec Issue Co-operation Manuf Syst 33(2/3):165–178

Erixon G (1996) Design for modularity. In: Huang GQ (ed) Design for X – concurrent engineering imperatives. Chapman & Hall, New York, pp 356–379

Erixon G, von Yxkull A, Arnström A (1996) Modularity – the basis for product and factory reengineering. Ann CIRP 45(1):1–6. https://doi.org/10.1016/S0007-8506(07)63005-4

Erlandsson A, Erixon G, Ostgren B (1992) Product modules – the link between QFD and DFA. In: 1992 International Forum on Design for Manufacture and

Assembly (DFMA), Boothroyd Dewhurst, Newport/Wakefield, 15–16 June 1992
Fujita K, Ishii K (1997) Task structuring toward computational approaches to product variety design. In: Proceedings of DETC'97. 1997 ASME design engineering technical conferences, 14–17 Sept 1997, Sacramento. DETC97/DAC-3766. American Society of Mechanical Engineers (ASME), New York
Henderson RM, Clark KB (1990) Architecture innovation: the reconfiguration of existing product technologies and the failure of established firms, Admistrative science quarterly. Spec Issue Technol Organ Innov 35(1):9–30. https://doi.org/10.2307/2393549
Hillström F (1994) Applying axiomatic design to interface analysis in modular product development. In: American Society of Mechanical Engineers, Design Engineering Division; Design Automation Committee (Publication) DE, vol 69-2, ASME, Proceedings of the 2th annual design automation conference, advances in design automation, Minneapolis, 11–14 Sept 1994, pp 363–372
Hubka V, Eder WE (1988) Theory of technical systems: a total concept theory for engineering design. Springer, Berlin
Ishii K, Eubanks CF, Di Marco P (1994) Design for product retirement and material life-cycle. Mater Des J 15(2):225–233
Ishii K, Juengel C, Eubanks CF (1995) Design for product variety: key to product line structuring. In: Proceedings of the 1995 design engineering technical conferences: presented at the 1995 ASME design engineering technical conferences, 17–20 Sept 1995, Boston. ASME, Design Engineering Division, New York. ASME, DE-Vol 83-2, pp 499–506
Jiao J, Tseng MM (2000) Fundamentals of product family architecture. Integr Manuf Syst 11(7):469–483. https://doi.org/10.1108/09576060010349776
Jiao J, Simpson TW, Siddique Z (2007a) Product family design and platform-based product development: a state-of-the-art review. J Intell Manuf 18(1):5–29. https://doi.org/10.1007/s10845-007-0003-2
Jiao J, Gershenson JK, Michalek JJ (2007b) Managing modularity and commonality in product and process development. Concurr Eng Res Appl 15(2):81–83. https://doi.org/10.1177/1063293X07079308
Karmarkar U, Kubat P (1987) Modular product design and product support. Eur J Oper Res 29(1):74–82. https://doi.org/10.1016/0377-2217(87)90195-0
Kohlhase N, Birkhofer H (1996) Development of modular structures: the prerequisite for successful modular products. J Eng Des 7(3):279–291. https://doi.org/10.1080/09544829608907941
Krause FL, Kimura F, Kjellberg T, Lu SC-Y et al (1993) Product modelling. Ann CIRP 42(2):695–706. https://doi.org/10.1016/S0007-8506(07)62532-3
Kusiak A, Huang C-C (1996) Development of modular products. IEEE Trans Components Packag Manuf Technol, Part A 19(4):523–538. https://doi.org/10.1109/95.554934
Lanner P, Malmqvist J (1996) An approach towards considering technical and economic aspects in product architecture design. In: Proceedings of the 2nd WDK-workshop on product structuring, TU Delft, The Netherlands, 3–4 June 1996
Meyer MH (1997) Revitalize your product lines through continuous platform renewal. Res Technol Manag 40(2):17–28
Meyer MH, Lehnerd AP (1997) The power of product platforms: building value and cost leadership. Free Press, New York
Newcomb PJ, Bras B, Rosen DW (1996) Implications of modularity on product design for the life cycle. J Mech Des 120(3):483–490. https://doi.org/10.1115/1.2829177
Pahl G, Beitz W (1996) Engineering design: a systematic approach, 2nd edn (trans: Wallace K). Springer, London
Pimmler TU, Eppinger SD (1994) Integration analysis of product decompositions. In: Proceedings of ASME design theory and methodology conference, Minneapolis, Sept 1994, DE-Vol 68, ASME, New York, pp 343–351. http://web.mit.edu/eppinger/www/pdf/Pimmler_DTM1994.pdf. Accessed 29 Dec 2016
Simon HA (1981) The sciences of the artificial. MIT Press, Cambridge, MA
Simpson TW (2004) Product platform design and customization: status and promise. AI EDAM 18(1):3–20. https://doi.org/10.1017/S0890060404040028
Starr MK (1965) Modular production-a new concept. Harv Bus Rev 43(6):131–142
Steward DV (1981) Systems analysis and management: structure, strategy and design. Petrocelli Books, New York
Suh NP (1990) The principles of design. Oxford University Press, New York
Thevenot HJ, Simpson TW (2006) Commonality indices for product family design: a detailed comparison. J Eng Design 17(2):99–119. https://doi.org/10.1080/09544820500275693
Ulrich KT (1994) Fundaments of product modularity. In: Dasu S, Eastman C (eds) Management of design. Springer, New York, pp 219–231. https://doi.org/10.1007/978-94-011-1390-8_12
Ulrich K (1995) The role of product architecture in the manufacturing firm. Res Policy 24(3):419–440. https://doi.org/10.1016/0048-7333(94)00775-3
Ulrich KT, Eppinger SD (1995) Product design and development. McGraw-Hill, New York
Ulrich KT, Eppinger SD (2000) Product design and development, 2nd edn. McGraw-Hill, New York

## Modularity

► Modular Design

# Molecular Dynamics

Fengzhou Fang[1,2] and Pengzhe Zhu[1]
[1]State Key Laboratory of Precision Measuring Technology and Instruments, Centre of MicroNano Manufacturing Technology, Tianjin University, Tianjin, China
[2]Centre of MicroNano Manufacturing Technology (MNMT-Dublin), University College Dublin, Dublin, Ireland

## Synonyms

Atomistic modeling; Atomistic simulation; MD; Molecular dynamics simulation

## Definition

Molecular dynamics (MD) method is a computer simulation technique by which the atomic trajectories of a system of N particles are generated by numerical integration of Newton's equation of motion, for specific interatomic potentials, with certain initial conditions and boundary conditions. MD can provide atomistic details of a wide range of processes and systems. Here MD is employed to study the material removal mechanism in nanometric cutting process.

## Theory and Application

### Introduction

Since the first paper reporting MD simulation was published (Alder and Wainright 1957), MD has been widely employed in a number of scientific fields such as physics, chemistry, biology, and materials science. Research on MD simulations of cutting started in the early 1990s and has attracted more and more attention recently.

### Theory

There are five main ingredients to a MD simulation, which are boundary condition, initial condition, interaction potential, integrator, and property calculation.

#### Boundary Condition

Generally, there are two major types of boundary conditions: isolated boundary condition (IBC) and periodic boundary condition (PBC). In IBC, the system is presumed to be surrounded by vacuum and the particles just interact among themselves. In PBC, the N-particle cell is surrounded by infinitely replicated, periodic images of itself. Therefore a particle may interact not only with particles in the same cell but also with particles in adjacent image cells. It should also be noted that in a system mixed boundary conditions can be adopted. That is to say, the system is assumed to be periodic in some directions but not in the others.

#### Initial Condition

The initial condition means the initial particle positions and velocities of the modeling system. It is easy to generate initial conditions for crystalline solids, but it would take some work for liquids and amorphous solids. A common strategy to create a liquid configuration is to melt a crystalline solid. The amorphous solid configuration is usually obtained through a melting and quenching simulation.

#### Interaction Potential

The motions of particles obey the Newton's equations of motion:

$$m_i \frac{d^2 \vec{r_i}}{dt^2} = \vec{F} \equiv -\frac{\partial U}{\partial \vec{r_i}} \qquad i = 1,2,\ldots,N \tag{1}$$

The forces are usually derived as the gradient of a potential energy function $U$ which depends on the positions of the particles. Therefore the potential energy function determines the dynamics of particles in the system. In some cases, MD simulations are designed to predict the behavior of generic atoms or particles. Thus, simple (two-body) pair potentials such as Lennard–Jones (LJ) potential and Morse potential would be adopted. To better reproduce the real material properties, more complicated many-body empirical potentials have been developed. For example, embedded atom method (EAM) potential can accurately describe the interactions between metal atoms. For EAM potential, the total potential energy of a system is expressed as

$$E_{\mathrm{tot}} = \frac{1}{2}\sum_{ij}\Phi_{ij}(r_{ij}) + \sum_{i}F_i(\rho_i) \qquad (2)$$

where $\Phi_{ij}$ is the pair potential between atoms $i$ and $j$, and $F_i$ is the embedded energy of atom $i$. $\rho_i$ is the host electron density at site $i$ induced by all other atoms in the system, which is given by

$$\rho_i = \sum_{j \neq i}\rho_j(r_{ij}) \qquad (3)$$

Other many-body potentials include Stillinger–Weber potential, Tersoff potential, reactive empirical bond order (REBO) potential, charge-optimized many-body (COMB) potential, and ReaxFF potential.

Generally speaking, it is hard to say which potentials are "good" or "bad"; the choice depends on the purpose of the study. The principle is to identify potentials that can reproduce the desired material properties and then choose the simplest one.

### Integrator

Equation 1 is a set of second-order, nonlinear ordinary differential equations, which can be solved numerically in MD simulations. Popular time-integration algorithms employed in MD simulations are Verlet algorithm, leap-frog algorithm, velocity Verlet algorithm, Beeman algorithm, and predictor–corrector algorithm, which can be found in the literatures (Allen and Tildesley 1987; Rappaport 1995; Li 2005). The time steps in the integration are in the range of a few femtoseconds ($10^{-15}$ s).

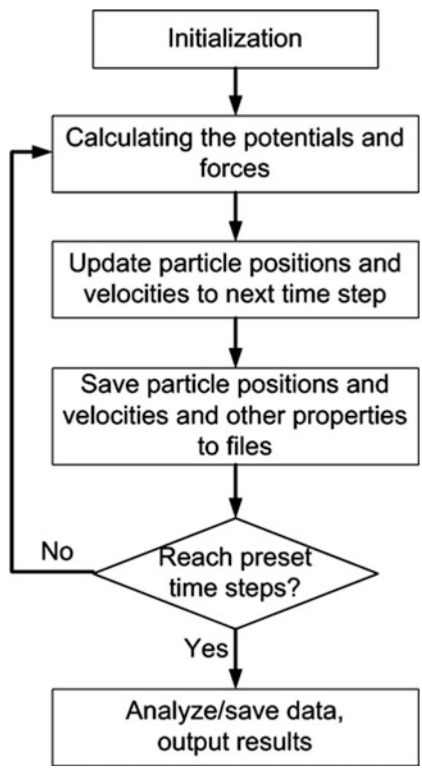
### Property Calculation

Generally the properties that can be computed in MD simulations can be roughly divided into four categories: (1) structural characterization, such as radial distribution function, dynamic structure factor, etc.; (2) equation of state, such as free-energy functions, phase diagrams, thermal expansion coefficient, etc.; (3) transport, such as viscosity, thermal conductivity (electronic contribution excluded), correlation functions, diffusivity, etc.; and (4) nonequilibrium response, such as friction, plastic deformation, pattern formation, etc.

The flowchart of a typical MD program is shown in Fig. 1.

## Application

MD simulations have been widely adopted to study the nanometric cutting, grinding, polishing, and nanoindentation processes since the early 1990s. A typical example of MD simulations of nanometric cutting is shown in Fig. 2 (Fang et al. 2007). The model consists of a monocrystalline silicon workpiece and a diamond cutting tool. The dimensions of the silicon are 16.3 nm × 19.6 nm × 6.5 nm (l × h × t). The cutting tool with a radius of 5 nm moves at a speed of 24.5 m/

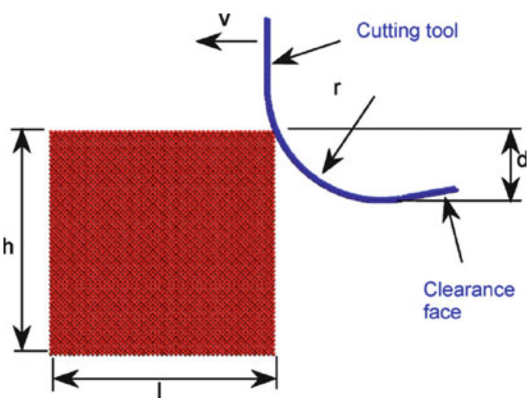



**Molecular Dynamics, Fig. 1** Flowchart of a typical MD program

M

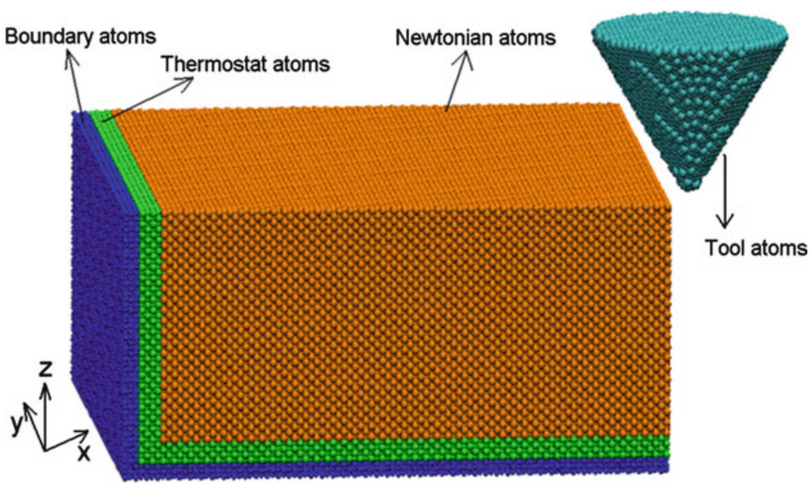
s. Rake angle and clearance angle are 0°and 10°, respectively. Tersoff potential was used to describe the interactions between atoms. The cutting depths are selected at 1 nm, 3 nm, and 5 nm for the simulation.

It is found that when the depth of cut is 1 nm, the contact area between material and cutting tool is very small. The atoms are not removed and only piled up in front of the cutting tool. There are elastic and plastic deformations on the workpiece surface. With an increase in cutting depth to 5 nm, more atoms are squeezed by the cutting tool. The excess atoms are piled up in front of the rake surface. The workpiece material is extruded out from the rake face of the cutting tool. The MD simulation results demonstrate that the chip formation in nanometric machining is mainly based on extrusion rather than shearing in conventional machining.




**Molecular Dynamics, Fig. 2** Schematic diagram of MD cutting model

Figure 3 shows another typical example of MD simulation of AFM-based nanometric cutting (Zhu et al. 2010). The model consists of a face-centered cubic (FCC) single-crystal copper workpiece and a rigid diamond tool. The size of the workpiece is 50a × 50a × 25a, where a is the lattice constant of Cu (a = 0.3615 nm). The three orientations of workpiece are in x-[100], y-[010], and z-[001]. The cutting is conducted along the [−1 0 0] direction on the (001) surface of the workpiece. The workpiece includes three kinds of atoms: boundary atoms, thermostat atoms, and Newtonian atoms. The motions of thermostat atoms and Newtonian atoms obey classical Newton's second law. The Newton's equations of motion are integrated with a velocity Verlet algorithm with a time step of 1 fs. The three layers of boundary atoms at the left and the bottom of the workpiece are kept fixed in space to reduce edge effect. The next three layers of atoms adjacent to the boundary atoms at the left and the bottom of the workpiece are thermostat atoms. The bulk (initial) temperature of the workpiece is 293 K. During MD simulations, heat dissipation is carried out by keeping the thermostat atoms at a constant temperature of 293 K by velocity scaling method. Periodic boundary conditions are imposed in the y direction.




**Molecular Dynamics, Fig. 3** Model of MD simulation of AFM-based cutting

The diamond tool created from perfect diamond atomic lattices has a configuration of a cone shape with a tool angle of 60°. For the Cu–Cu interaction between workpiece atoms, the EAM potential is used. As the tool is treated as a rigid body, the C–C interactions between tool atoms are ignored. For the Cu–C interaction, the Morse potential is adopted.

The MD simulation of cutting process consists of two stages: the relaxation stage and the cutting stage. The effects of tool geometry, cutting depth, cutting velocity, and temperature on material removal and deformation and cutting forces are thoroughly studied.

The MD simulation results can be analyzed to explore the physics of nanometric cutting, such as the microstructure change of workpiece material, the material removal and chip formation mechanisms, the stress and temperature distribution and the effect of lubrication, and so on. In summary, MD simulation is a powerful tool to help people understand the physics of nanomachining process.

## Cross-References

▶ Abrasive Material
▶ Atomic Force Microscopy
▶ Cutting Edge Geometry
▶ Cutting Fluid
▶ Cutting Temperature
▶ Cutting, Fundamentals
▶ Grinding
▶ Molecular Dynamics for Cutting Processes
▶ Material Flow

## References

Alder BJ, Wainright TE (1957) Phase transition for a hard sphere system. J Chem Phys 27(5):1208
Allen MP, Tildesley DJ (1987) Computer simulation of liquids. Clarendon, Oxford
Fang FZ, Wu H, Zhou W, Hu XT (2007) A study on mechanism of nano-cutting single crystal silicon. J Mater Process Technol 184:210–407
Li J (2005) Basic molecular dynamics, Chap. 2.8. In: Handbook of materials modeling. Springer, Dordrecht, pp 565–588
Rappaport DC (1995) The art of molecular dynamics simulation. Cambridge University Press, Cambridge, UK
Zhu PZ, Hu YZ, Ma TB, Wang H (2010) Study of AFM-based nanometric cutting process using molecular dynamics. Appl Surf Sci 256:7160–7165

# Molecular Dynamics for Cutting Processes

Rüdiger Rentsch
Leibniz IWT, Bremen, Germany

## Synonyms

Atomistic modeling; MD; Molecular dynamics; Statistical mechanics

## Definition

The molecular dynamics method is a numerical method describing the micro mechanical and thermodynamic properties of a sample volume of material consisting of interacting atoms and/or molecules for a period of time. Here molecular dynamics is used to simulate the material removal processes at the atomic or nanometer level.

M

## Theory and Application

### Introduction

Being originally developed for studies in condensed matter physics (Alder and Wainright 1957), it was gradually extended to many applications on phase transformations, dynamics, and structures of crystals, molecules, and fluids (Yonezawa 1990). The first pioneering applications of molecular dynamics (MD) on atomic level or nanoindentation and for material removal processes were published in the 1990s. This development was pushed by the manufacturing technology which had reached the nanometer-level precision in the fields of semiconductor industry, precision machining, and micromachining already before (Ikawa et al.

1991). The largest studied MD models have reached the level of 320 billion atoms by the year 2006 (Kadau et al. 2006).

## Theory

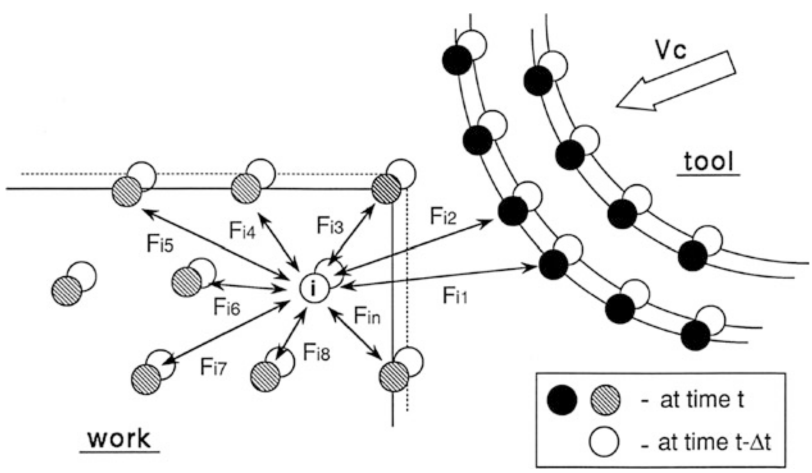
In MD the considered microscopic material properties and the underlying constitutive physical equations of state provide a sufficiently detailed and consistent description of the micro mechanical and thermal state of the modeled material to allow for the investigation of the local tool tip/workpiece contact dynamics at the atomic level (Hoover 1991). The description of microscopic material properties considers, e.g., microstructure, lattice constants and orientation, chemical elements, and the atomic interactions. The following table lists the representation of material properties and physical principles in MD, which have to be described numerically in an efficient way to allow for large-scale systems, i.e., models with hundred thousands, millions, or even billions of particles (Table 1).

The microstructural representation requires an initial configuration of the particles, which can be, in principle, arbitrary (e.g., amorphous, granular, single crystalline, or molecular). Usually their mass is concentrated in their center of gravity, and its coordinates determine the position of the particle in space and their distance relative to each other (cf. Fig. 1).

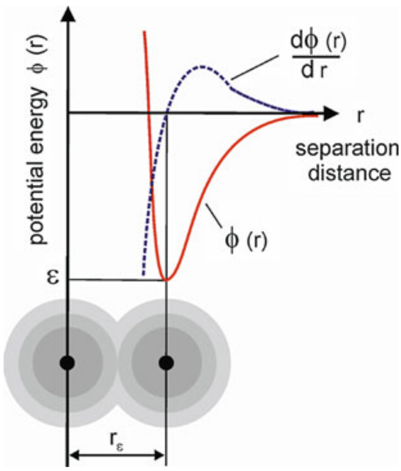
For the MD calculation, i.e., the free dynamic evolution of the whole system of particles, energetic functions are needed, which describe the particle-particle interactions between all types of chemical elements. All material-specific information is stored in these so-called potential energy functions, and the equilibrium conditions result from it. In simple cases, it might be sufficient to use potential energy functions, which are only a function of separation distance between two neighboring atoms, the so-called *pair potentials*, as shown in Fig. 2. More complex approaches and material property representation, like for most metals, require the consideration of local composition, bonding angles, and others (refer to *bond-order* and *embedded atom potentials EAM* in Hoover 1991 and in Rappaport 1995). The equilibrium bonding distance between two particles requires the potential energy function to be

**Molecular Dynamics for Cutting Processes, Table 1** Material properties and physical principles in MD

| Physical principles and material properties | Representation in MD |
|---|---|
| Microstructure | Crystal structure, molecules (initial) |
| Micro mechanics | Atomic/molecular interaction |
| Dynamics | Equations of motion (numerical description) |
| Thermodynamics | Energy balance of the system |
| Boundary conditions (additional constraints) | Micro mechanical model boundaries (support) |




**Molecular Dynamics for Cutting Processes, Fig. 1** Interaction between atoms of two bodies minimum at distance $r_\varepsilon$. The energy will increase in both cases, if both particles get closer or more distant to each other. However, for large separation distances, the potential energy asymptotically approaches to zero on which the bond is considered being broken. The derivative of the potential function with respect to distance represents the bonding force acting between the particles. It is negative, i.e., repulsive, at close distance, zero at equilibrium bonding distance, and positive (i.e., attractive) at larger distances than the equilibrium bonding distance.

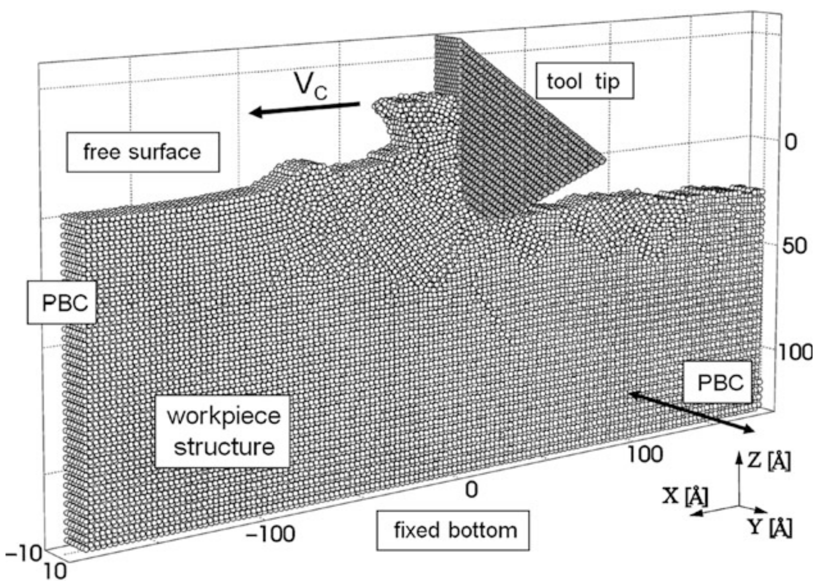



**Molecular Dynamics for Cutting Processes, Fig. 2** Potential energy between two interacting particles

In MD the trajectory of the systems constituents through space and over time is calculated. For this being possible, an equation of motion for the particles is necessary. Most popular is Newton's equation of motion stating that the sum of forces acting on a particle is equal to the product of its mass and its vector of acceleration. Integrating this equation once with respect to time reveals the velocity vector and, for the second time, the change of position in space at the given time. Numerically efficient approximations for the integration of the equation of motion (like the Verlet, the Predictor-Corrector, or the Newton-Raphson algorithm) can be found in the literature (Allen and Tildesley 1987; Rappaport 1995). Following the motion of the single particle over time requires time steps in the range of a few femtoseconds ($10^{-15}$ s).

The total energy balance of the MD model and its energy exchange with the not-modeled environment is calculated using thermodynamics formulations (for details refer to Allen and Tildesley 1987; Hoover 1991; Rappaport 1995). Balance of the energy of the system is important for nanocutting and nanoindentation simulations in particular, since the interaction between tool and work adds mechanical energy into the system, which






**Molecular Dynamics for Cutting Processes, Fig. 3** Orthogonal MD nano-cutting process simulation using a 3D model – cutting on a {001} surface along <110> direction of a copper crystal (Rentsch 1999, 2009) otherwise could result in an uncontrolled temperature rise of the system and particles.

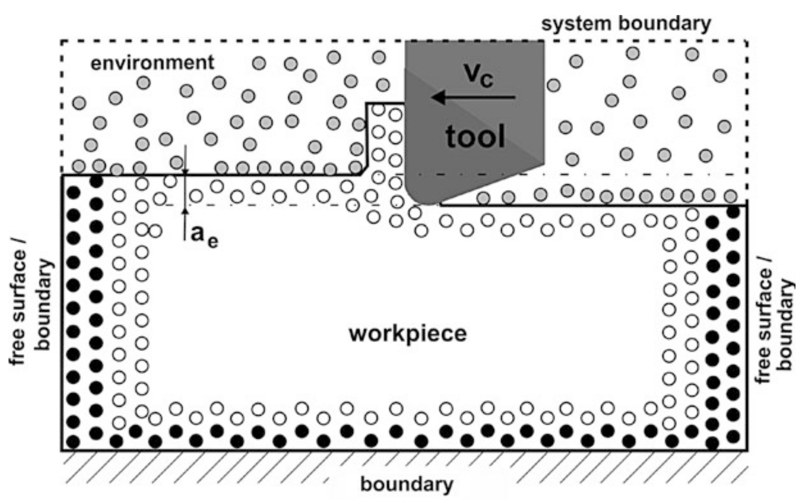
For nano-cutting and nanoindentation simulations, additional boundary conditions and constraints could be necessary. Here at least the thrust forces, possibly the cutting forces as well as the working tool or indenter must be balanced, i.e., supported. For this purpose usually fixed boundaries or fixed atoms are introduced at the model bottom, i.e., on the opposite side of the tool/workpiece contact surface.

## Application

Many MD nano-cutting, grinding, and nanoindentation simulations have been carried out already, and frequently more are being published. Due to the representation starting at the atomic level, the real size of the models, i.e., number of atoms, as well as the process observation time is limited. However, the main obstacle to a broader application in engineering science is often the lack of the necessary potential functions for all possible interactions of typical engineering materials like alloyed steels, although potential functions for alloys are being developed steadily. This drawback is sometimes bypassed by carrying out so-called *first principle* or ab initio MD calculations, in which even the electronic structure of the atoms is included at the expense of limiting the absolute size and time of the models even more.

An example for an MD nano-cutting simulation for orthogonal cutting process conditions is shown in Fig. 3. Here single-crystalline copper is cut by a diamond cutting edge (tool tip) at a cutting velocity $v_c$ of 100 m/s. The orientation of the copper crystal ({001} surface) and the cutting direction were chosen in a way (along <110> direction) that its orthogonal setup allows for proper dislocation slip formation across the periodic boundaries (PBC: model boundaries in X and Y direction). The model considered about 80,000 fully dynamic work and tool atoms and thermostat boundaries close to the outer boundaries to control the process temperature. For the Cu/Cu interactions, an EAM potential was employed, because of their better description of metallic material properties. The C/C interaction in the diamond tool was approximated using a pair potential with the bond strength of diamond. The atoms were placed on face-centered cubic lattice sites with an adjusted lattice constant in order to account for the correct atom density of diamond and, thereby, for a reasonable reaction intensity at the tool/work contact zone. A weak, adhesive potential for the tool/work interaction was chosen (for more details see Rentsch 1999, 2009).

The simulation results can be analyzed in a broad way exploring the underlying physics: structure analysis of the crystal changes, cutting forces, cutting temperature distribution and their change over time, transient effects of the material




**Molecular Dynamics for Cutting Processes, Fig. 4** Concept for an MD nano-cutting simulation model considering a cutting fluid (Rentsch and Inasaki 2006) removal mechanisms, and more. Although the model in Fig. 3 starts with a single-crystal structure, the more universal material representation in MD allows further to go beyond ideal, single-crystalline structures and to consider also poly-crystals, defect structures, material defects like microcracks, and pre-machined or otherwise constrained workpiece models, and non-smooth surfaces as well as various application specific boundary conditions may be applied (Allen and Tildesley 1987; Hoover 1991; Rappaport 1995).

Most of the published results considered models with ideal single-crystal structures as starting configuration and vacuum conditions since no atmosphere or fluids were included. Although in micro-cutting and precision machining minimum quantity lubrication (MQL) can be applied, the conditions are not that ideal. A rather strong field of MD application deals with fluids, molecules, and polymers. First extensions toward fluids in MD cutting simulations have been carried out already considering a concept as shown in Fig. 4.

## Cross-References

▶ Abrasive Material
▶ Atomic Force Microscopy
▶ Bonding
▶ Cutting Edge Geometry
▶ Cutting Fluid
▶ Cutting Temperature
▶ Cutting, Fundamentals
▶ Dynamics
▶ Grinding
▶ Material Flow
▶ Micromachining

## References


Alder BJ, Wainright TE (1957) Phase transition for a hard sphere system. J Chem Phys 27(5):1208

Allen MP, Tildesley DJ (1987) Computer simulation of liquids. Clarendon, Oxford

Hoover WG (1991) Computational statistical mechanics, studies in modern thermodynamics 11. Elsevier Science, Amsterdam

Ikawa N, Donaldson RR, Komanduri R, Koenig W, McKeown PA, Moriwaki T, Stowers IF (1991) Ultraprecision metal cutting – the past, the present and the future. Ann CIRP 40(2):587–594

Kadau K, Germann TC, Lomdahl PS (2006) Molecular dynamics comes of age: 320 billion atom simulation on BlueGene/L Intern. J Mod Phys C 17(12):1755–1761

Rappaport DC (1995) The art of molecular dynamics simulation. Cambridge University Press, Cambridge, UK

Rentsch R (1999) Atomistic simulation and experimental investigation of ultra precision cutting processes. MRS Proc 578:261–266

Rentsch R (2009) Molecular dynamics of nanoscale cutting. In: Davim JP, Jackson MJ (eds) Nano and micromachining. ISTE/Wiley, London/Hoboken, pp 1–26

Rentsch R, Inasaki I (2006) Effects of fluids on the surface generation in material removal processes – molecular dynamics simulation. Ann CIRP 55(1):601–604

Yonezawa F (1990) Molecular dynamics simulations. Springer, Berlin


# Molecular Dynamics Simulation

▶ Molecular Dynamics



# Monetary Value

▶ Cost

# Monitoring

Hans-Christian Möhring
Institute for Machine Tools, University of Stuttgart, Stuttgart, Germany

## Synonyms

Monitoring algorithm, Monitoring strategy, Monitoring system

## Definition

“Monitoring” makes the conditions of processes, tools, machines and machine components, and workpieces visible, processible, analyzable, and describable by means of characteristic values obtained during the running process. Monitoring possesses the detection of the functioning or deviation of actual values from the planned values over a certain period of time. Thus, it enables the distinction concerning proper conditions or faulty condition. Monitoring allows to obtain the input-output causalities of processes. It provides the basis for adaptive control by adjusting process input parameters. A monitoring system comprises elements for data acquisition, signal (pre)processing, data assessment, and decision making. The monitoring strategy is the applied method for signal acquisition and assessment, in which the monitoring algorithm defines structure rules of the monitoring strategy.

## Theory and Application

### Theory

#### Brief History of Key Publications in CIRP

- 1976: Micheletti et al.: Tool wear monitoring in metal cutting
- 1983: Tlusty, Andrews: Sensors for unmanned machining
- 1988: Tönshoff et al.: Monitoring and control
- 1995: Byrne et al.: Tool condition monitoring
- 1995: Teti: Tool condition monitoring literature database
- 2010: Teti et al.: Advanced monitoring of machining operations (this entry partly refers to this CIRP keynote paper)

#### Monitoring Scopes

Monitoring is applied in several domains of production, e.g., in cutting, grinding, forming, and assembly. In this entry, the term monitoring is explained using predominantly the example of cutting. Most aspects also apply to other manufacturing processes.

Basically, monitoring can refer to either the process condition or the machine condition (Fig. 1).

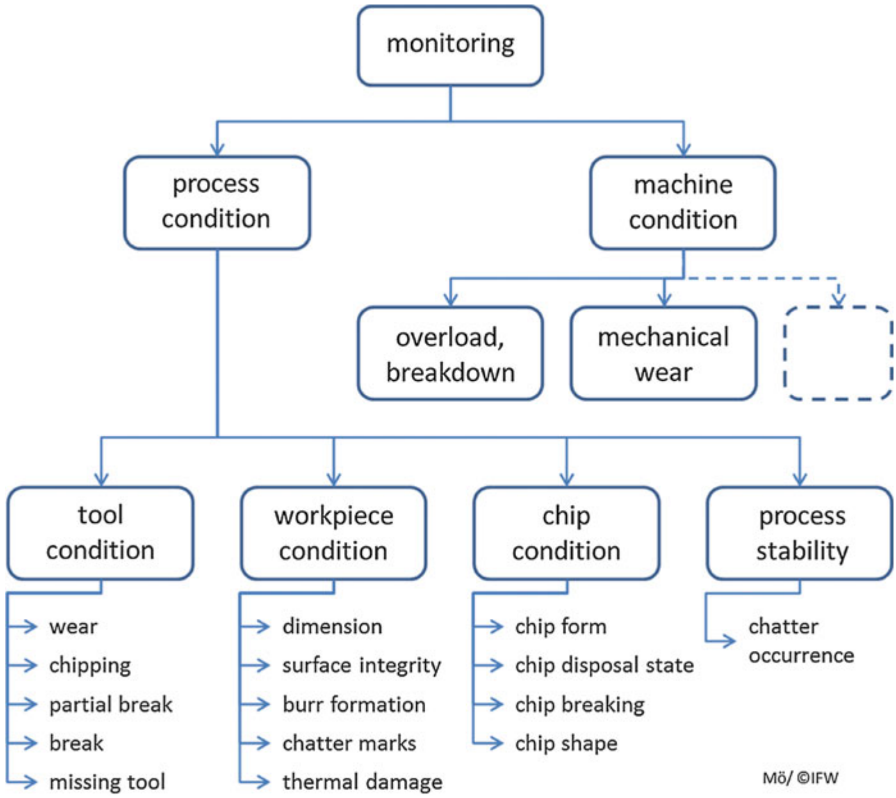
Regarding machine condition monitoring, sensor and control data is collected and processed in order to perceive overload or breakdown of components (e.g., thermal damage of motors), to identify and observe mechanical wear and its progress (e.g., in bearings, ball screws, and linear guidings), to detect malfunction (e.g., leakage of seals), and for other aspects related to the function of the machine and its components. Machine and control internal sensors and information can also be used for process condition monitoring and assessment of process results (e.g., geometric measuring inside a machine tool using a touch probe and data form linear scales of the machine axes).

Following the understanding of a cutting process as a system (see entry "Cutting, Fundamentals"), in process condition monitoring, information from input operators (e.g., set variables), process interaction values, and output operators is used. Process condition monitoring can be structured in monitoring of tool condition, workpiece condition, chip condition, and the observation of process stability (Dimla 2000; Teti et al. 2006). Process stability or chatter can be monitored at tool or workpiece side of the process. Special applications also use monitoring systems for the identification of workpiece material, heat treatment condition, or defined process events (e.g., tool-workpiece contact).

The aim of process monitoring in general is to observe whether the desired process results are achieved acceptably by the running process, whether the process runs in a reproducible way or whether failures occur (Dornfeld and Lee 2008; Dornfeld et al. 2006). This is particularly necessary in unmanned manufacturing. In mass production, monitoring allows the detection of disturbances which lead to unforeseen conditions and which could provoke costly system breakdown. In single piece or small batch production of large and expensive workpieces, monitoring focuses on the detection of effects which lead to damages at the workpieces. Monitoring can also support ramp-up and setup procedures (Byrne et al. 2004).

#### General Structure of Process Monitoring Systems

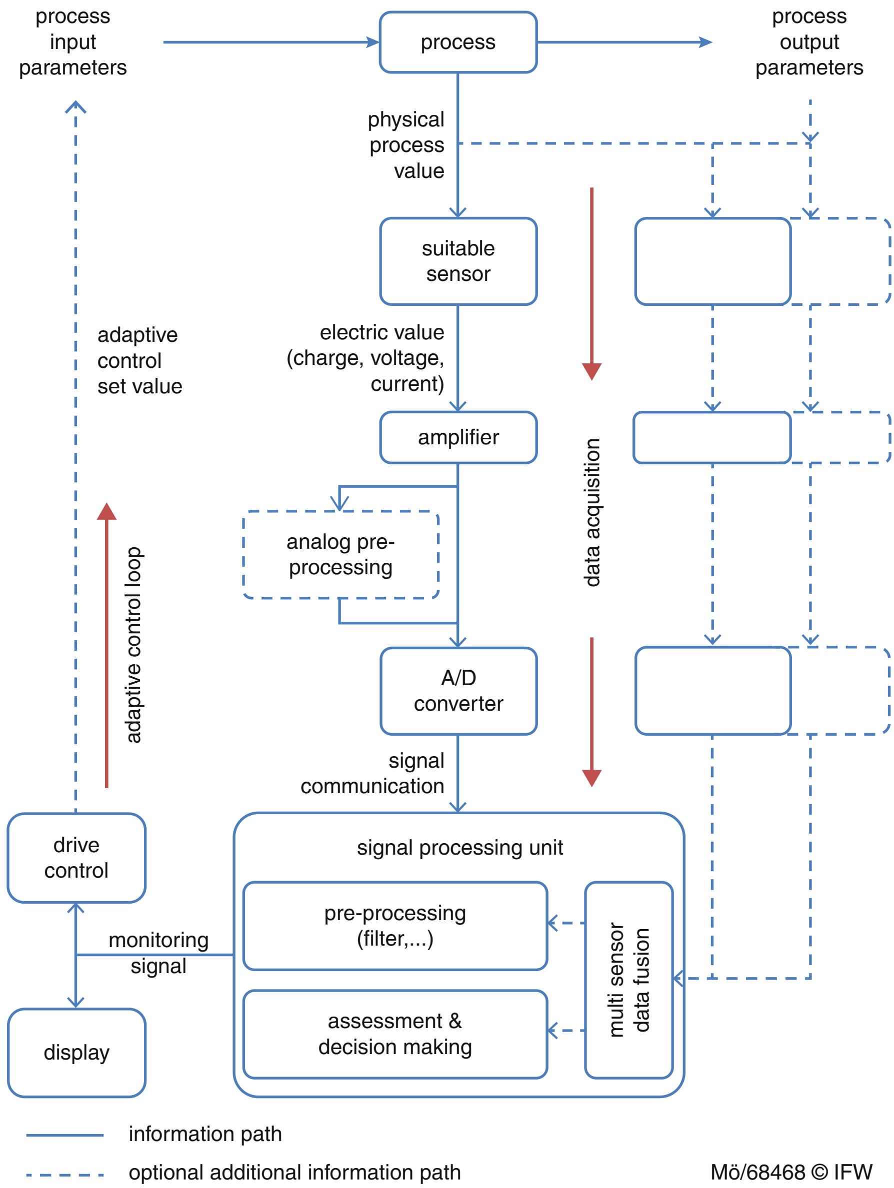
The description of the general structure of process monitoring systems (Fig. 2) again starts with the




**Monitoring, Fig. 1** Basic classification of monitoring applications in cutting

general view on a cutting process with input parameters (e.g., NC-code, set values like spindle speed and feed rate, tool information like number of cutting edges and diameter of a milling tool, and workpiece information like material data or initial geometry), process interaction values (e.g., forces, torques, temperatures, vibration and acoustic emission, and radiation), and output parameters (e.g., workpiece geometry, surface conditions, and tool wear condition). Input parameters can be used for the setup and parameterization of monitoring systems. Output parameters can be used as monitoring values if monitoring has no real-time functionality. Output parameters are also needed for finding correlations between monitoring values (which are collected during the running process) and process results (e.g., surface roughness), as well as for validation of monitoring strategies. Common monitoring systems use in-process monitoring values gathered from the process interactions.

Physical process values – such as force, torque, acceleration, vibration speed and energy, acoustic emission, audible sound energy, temperature, and heat radiation – are recorded by suitable sensors which transform the physical value into an electric value (charge, voltage, current) (Hundt et al. 1994; Jemielniak 2001; Jemielniak and Arrazola 2008; Karpuschewski et al. 2000; Klocke and Rehse 1997). The sensitivity of information collection depends on the information path between the location at which the physical value arises (e.g., force and acceleration in the tool contact zone) and the location of the sensor, the sensor sensitivity, and the sensor bandwidth. The quality of a sensor information also depends on the influence of disturbing values and the signal-to-noise ratio. In most cases, the electric value which is generated by the sensor has to be amplified for further communication, processing, and analysis. Communication of sensor signals from rotating parts or locations which are difficult to access can utilize slip rings, inductive




**Monitoring, Fig. 2** General structure of process monitoring systems

coupling, radio-frequency transmission, or even transmission via a coupling fluid like the coolant supply (Inasaki 1998).

The amplified analog sensor signal can be pre-processed (e.g., using analog filters) or is directly transmitted to an analog digital converter (A/D converter), in which a digital signal is generated by sampling the analog signal. The sampling rate of the A/D converter limits the bandwidth of the entire information collection. Analog and digital sensor information can be communicated continuously or intermittently using sensor wires, bus systems, wireless communication standards, or optoelectronic devices.

The collected sensor information is communicated to a signal processing unit, in which further filtering, data processing and analysis, as well as the derivation of the monitoring result are performed. The information chain from the collection of the physical process value to the signal processing unit constitutes the data acquisition part of a process monitoring system. Instead of only one single-sensor information chain, several sensors and information chains can be used at the same time. Multiple sensor information can then be processed separately or in a combined way by multi-sensor data fusion.

The signal processing unit can consist of a local data processing system (e.g., a microcontroller), a special separated or control-integrated monitoring device, or an industrial or standard personal computer. Signal processing and data assessment in order to derive the monitoring result and to allow decision making (e.g., distinction between acceptable or unacceptable process condition) constitute the other main parts of a monitoring system (besides data acquisition). Basically, the signal processing unit can show the processed sensor information and the derived monitoring signal (e.g., the excess of a predefined threshold value) to the user via a display.

In addition, sophisticated monitoring systems enable the computation of adaptive control set values (e.g., adapted spindle speed or feed rate) which can be used as process input parameters. This constitutes the adaptive control loop.

### Sensors for Monitoring

Measuring techniques for monitoring can be categorized into direct and indirect approaches (Teti et al. 2010). In the direct approach, the actual quantity of the respective parameter (e.g., tool wear) is measured. In indirect approaches, auxiliary quantities (e.g., cutting force) are measured and the actual quantity is deduced by appropriate signal processing strategies. Indirect approaches are less accurate but also less complex and therefore more practical.

Besides various sensor types, machine internal control values are suitable information sources for process monitoring (Lange 2004).

Machine internal information sources:

- Position measurement systems and encoders
- Main spindle current/power (Axinte and Gindy 2004; Pritschow et al. 1999)
- Feed motor current/power (Altintas 1992)
- Command values of electromagnetic bearings (Auchet et al. 2004)

Sensors for force and torque measuring:

- Strain gauges
- Piezoelectric force/torque transducer
- Capacitance sensors to detect spindle shaft displacement due to cutting load (Albrecht et al. 2005)
- Special force sensors (Teti et al. 2010): micro force sensor, surface acoustic wave sensors, and Villari sensor

Online correction of force measurement errors can be accomplished by compensation of calculable inertia influences or adaptive filtering.

Sensors for vibration, acoustic emission (AE), and audible sound energy measuring:

- Piezoelectric vibration and AE sensors
- Capacitance AE sensors
- Fiber optics (Caralon et al. 1997)
- Microphone

Sensors for temperature and heat radiation measuring:

- Resistance temperature sensor
- Thermocouple
- Thermographic sensor
- Pyrometer

Extensive information about temperature measurement in machining can be found in Davies et al. (2007).

Other sensors:

- Vision systems for monitoring tool condition (Kurada and Bradley 1997)

A comprehensive overview about sensors in manufacturing applications and monitoring is given by Tönshoff and Inasaki (2001) and Karpuschewski (2001). An ongoing field of developments and research is the integration of sensors into machine structures for monitoring purposes (Byrne and O'Donnell 2007; Möhring et al. 2010).

### Signal (Pre)Processing

Following Teti et al. (2010), signal processing for process monitoring applications comprises:

- Signal preprocessing (amplification, filtering, A/D conversion, segmentation, signal transformation)
- Extraction of signal or signal transform features changing with tool or process conditions
- Feature selection

Analog signals are often preprocessed using low-pass or band-pass filters in order to keep the signal in a processible frequency range or to focus on the most interesting frequency range. Kalman filtering can be applied for compensation of disturbing effects. Acoustic emission signals are usually demodulated to RMS (root mean square) signals to obtain a low-frequency variable. Signal transformation means a transformation of sensor signals into frequency or time-frequency domain (e.g., by Fourier or Wavelet transformation) for further analysis. Segmentation of sensor signals conduces to extract different process states (e.g., actual cutting edge engagement) in order to maximize information content and to achieve comparable data.

Extraction of monitoring features can be conducted in time domain or frequency and time-frequency domain. The aim of feature extraction is to derive characteristic values which describe the relevant information about the process conditions.

Commonly used characteristic values extracted from time domain signals are arithmetic mean, average value, magnitude, effective value, variance, skewness, kurtosis, signal power, peak-to-peak range, crest factor, ratios, and signal increments (Teti et al. 2010). Further time domain feature extraction strategies are time series modeling (autoregressive, moving average, autoregressive moving average), principal component analysis, singular spectrum analysis, and permutation entropy.

Feature extraction in the frequency domain is usually based on the fast Fourier transformation (FFT) or the short-time Fourier transformation (STFT). Considered features are amplitude of dominant spectral peaks, signal power in specific frequency ranges, energy in frequency bands, statistic features of band power spectrum, and frequency of the spectrum highest peak. The wavelet transformation (WT) is advantageous compared to the STFT and FFT with respect to the time and frequency resolution. It decomposes a signal through the wavelet scale function and scaled and shifted versions of the mother wavelet. WT is sometimes used for signal de-noising before applying another signal processing technique (Li et al. 1999; Kwak 2006; Teti et al. 2010). WT applications in process monitoring are described in Kunpeng et al. (2009).

Signal feature selection aims at choosing the most relevant information for a certain monitoring task. By analysis of sensor signal sensitivity with respect to process interaction values and the correlation between process output parameters and monitoring signal features, the most relevant data sets can be identified (Al-Habaibeh and Gindy 2000). In multi-sensor applications, dependencies between different sensor signals should be taken into account in signal feature selection.

### Multi-sensor Data Fusion

In multi-sensor data fusion, signals from different sensors and information sources are combined in order to get the desired information content, to improve sensitivity or signal-to-noise ratio, or to increase the robustness of a monitoring system ("robustness" here means the avoidance of false monitoring decisions caused by disturbances and noisy, diffuse, or uncertain signals or features). Direct fusion (fusion of data from a set of heterogeneous or homogeneous sensors, soft sensors, and history values of sensor data), indirect fusion (use of a priori knowledge and human input), and fusion of the outputs of the former can be distinguished (Teti et al. 2010). As an example, sensor fusion for process monitoring has been investigated where cutting force, vibration, AE, motor current, audible sound, and optical sensors have been combined. Often force values or respective motor currents are combined with vibration or AE signals in order to extend the information bandwidth and to improve sensitivity. The combination of strain gauges and temperature sensors allows more accurate measuring due to error compensation (Shinno and Hashizume 1997). A Kalman filter is used in Möhring et al. (2010) for sensor data fusion of distributed strain gauges and force sensors in sensory machine tool components. Thus, a modular sensor architecture can be implemented.

### Assessment and Decision Making

The final goal of monitoring is the assessment of the obtained process information and the derivation of a decision about the process, tool, or workpiece condition. In principle, the assessment of monitoring values and features can be based on:

- A comparison with predefined threshold values
- A comparison with "taught" threshold values or boundary lines, where teaching means the identification of reference values at acceptable process conditions
- A comparison with threshold values or boundary lines calculated by process simulation
- An analysis of the dynamic signal behavior (e.g., observing the gradient of a signal sequence or the appearance of features in the frequency domain)
- The statistical analysis of signals (utilizing the abovementioned filtering strategies)

In order to achieve a conclusion on process conditions, cognitive computing methods can be employed (Teti and Kumara 1997):

- Neural networks (Kuljanic et al. 2009; Sick 2002)
- Fuzzy logic (Balazinski and Jemielniak 1998)
- Genetic algorithms (Achichea et al. 2002)

Decisions derived by monitoring systems can initiate reactions (e.g., machine stop, adaptation of spindle or drive set values) in order to avoid critical process conditions (e.g., chatter) or severe damage of workpieces and machine components. In addition, long-term storage for statistic process control (SPC) purposes and documentation (e.g., to support certification of processes) can be reasonable.

## Cross-References


▶ Adaptive Control
▶ Chatter
▶ Chatter Prediction
▶ Control
▶ Cutting Temperature
▶ Drilling
▶ Grinding
▶ Grinding Monitoring
▶ Machine Tool
▶ Sensor (Machines)


## References


Achichea S, Balazinski M, Baron L, Jemielniak K (2002) Tool wear monitoring using genetically-generated fuzzy knowledge bases. Eng Appl Artif Intell 15:303–314

Albrecht A, Park S, Altintas Y, Pritschow G (2005) High frequency bandwidth cutting force measurement in milling using capacitance displacement sensors. Int J Mach Tools Manuf 45:993–1008

Al-Habaibeh A, Gindy N (2000) A new approach for systematic design of condition monitoring systems for milling processes. J Mater Process Technol 107:243–251

Altintas Y (1992) Prediction of cutting forces and tool breakage in milling from feed drive current measurement. J Eng Ind 114(4):386–392

Auchet S, Chevrier P, Lacour M, Lipinski P (2004) A new method of cutting force measurement based on command voltages of active electro-magnetic bearings. Int J Mach Tools Manuf 44:1441–1449

Axinte D, Gindy N (2004) Assessment of the effectiveness of a spindle power signal for tool condition monitoring in machining processes. Int J Prod Res 42(13): 2679–2691

Balazinski M, Jemielniak K (1998) Tool conditions monitoring using fuzzy decision support system. In: V. CIRP international conference on monitoring and automatic supervision in manufacturing, Miedzeszyn near Warsaw, 20–21 Aug, pp 115–122

Byrne G, O'Donnell GE (2007) An integrated force sensor solution for process monitoring of drilling operations. CIRP Ann Manuf Technol 56(1):89–92

Byrne G, Dornfeld D, Inasaki I, Ketteler G, König W, Teti R (1995) Tool condition monitoring – the status of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research and industrial application. CIRP Ann Manuf Technol 44(2):541–567
Byrne G, Dornfeld D, Denkena B (2004) Advancing cutting technology. CIRP Ann Manuf Technol 52(2):483–507
Caralon TA, Kidd SR, Hand DP, Wilcox SJ, Wilkinson P, Barton JS, Jones JDC, Reuben RL (1997) Acoustic emission monitoring of tool wear during the face milling of steels and aluminium alloys using a fibre optic sensor (parts 1 + 2). Proceedings of the institution of mechanical engineers, part b. J Eng Manuf 211(4): 299–309, 311–319
Davies MA, Ueda T, M'Saoubi R, Mullany B, Cooke AL (2007) On the measurement of temperature in material removal processes. CIRP Ann Manuf Technol 56(2):581–604
Dimla DE (2000) Sensor signals for tool-wear monitoring in metal cutting: a review of methods. Int J Mach Tools Manuf 40:1073–1098
Dornfeld D, Lee DE (2008) Precision manufacturing. Springer, New York
Dornfeld D, Min S, Takeuchi Y (2006) Recent advances in mechanical micromachining. CIRP Ann Manuf Technol 55(2):745–768
Hundt W, Leuenberger D, Rehsteiner F, Gygax P (1994) An approach to monitoring of the grinding process using acoustic emission (AE) technique. CIRP Ann Manuf Technol 43(1):295–298
Inasaki I (1998) Application of acoustic emission sensor for monitoring machining processes. Ultrason Int 36(1–5):273–281
Jemielniak K (2001) Some aspects of acoustic emission signal pre-processing. J Mater Process Technol 109: 242–247
Jemielniak K, Arrazola PJ (2008) Application of AE and cutting force signals in tool condition monitoring in micro-milling. CIRP J Manuf Sci Technol 1:97–102
Karpuschewski B (2001) Sensoren zur Prozeßüberwachung beim Spanen. Habilitationsschrift [Sensors for monitoring of material removal processes, habilitation thesis]. Fortschritt-Berichte VDI, Reihe 2, Nr. 581, Berichte aus dem Institut für Fertigungstechnik und Spanende Werkzeugmaschinen, Universität Hannover. VDI-Verlag, Düsseldorf
Karpuschewski B, Wehmeier M, Inasaki I (2000) Grinding monitoring system based on power and AE sensing. CIRP Ann Manuf Technol 49(1):235–240
Klocke F, Rehse M (1997) Intelligent tools through integrated micro systems. Prod Eng Res Dev 4(2):65–68
Kuljanic E, Sortino M, Totis G (2009) Development of an intelligent multi-sensor chatter detection in milling. Mech Syst Signal Process 23(5):1704–1718
Kunpeng Z, Wong YS, Hong GS (2009) Wavelet analysis of sensor signals for tool condition monitoring – a review and some new results. Int J Mach Tools Manuf 49:537–553
Kurada S, Bradley C (1997) A review of machine vision sensors for TCM. Comput Ind 34:55–72
Kwak JS (2006) Application of wavelet transform technique to detect tool failure in turning. Int J Adv Manuf Technol 28:1078–1083
Lange D (2004) Systems and strategies for control-system-integrated process and machine condition monitoring. In: CIRP international conference on high performance cutting, Aachen
Li X, Dong S, Yuan Z (1999) Discrete wavelet transform for tool breakage monitoring. Int J Mach Tools Manuf 39:1935–1944
Micheletti DF, König W, Victor HR (1976) In process tool wear sensor for cutting operations. CIRP Ann Manuf Technol 25(2):483–496
Möhring HC, Litwinski KM, Gümmer O (2010) Process monitoring with sensory machine tool components. CIRP Ann Manuf Technol 59(1):383–386
Pritschow G, Bretschneider J, Fritz S (1999) Reconstruction of process forces within digital servodrive systems. Prod Eng Res Dev 6(1):73–78
Shinno H, Hashizume H (1997) In-process monitoring method for machining environment based on simultaneous multiphenomena sensing. CIRP Ann Manuf Technol 46(1):53–56
Sick B (2002) On-line and indirect tool wear monitoring in turning with artificial neural networks: a review of more than a decade of research. Mech Syst Signal Process 16(4):487–546
Teti R (1995) A review of tool condition monitoring literature database. CIRP Ann Manuf Technol 44(2):659–666
Teti R, Kumara SRT (1997) Intelligent computing methods for manufacturing systems. CIRP Ann Manuf Technol 46(2):629–652
Teti R, Jawahir IS, Jemielniak K, Segreto T, Chen S, Kossakowska J (2006) Chip form monitoring through advanced processing of cutting force sensor signals. CIRP Ann Manuf Technol 55(1):75–80
Teti R, Jemielniak K, O'Donnell G, Dornfeld D (2010) Advanced monitoring of machining operations. CIRP Ann Manuf Technol 59(2):717–739
Tlusty J, Andrews GC (1983) A critical review of sensors for unmanned machining. CIRP Ann Manuf Technol 32(2):563–572
Tönshoff HK, Inasaki I (eds) (2001) Sensors applications. vol 1: sensors in manufacturing. Wiley-VCH, Weinheim
Tönshoff HK, Wulfsberg JP, Kals HJ, König W, van Luttervelt CA (1988) Development and trends in monitoring and control of machining process. CIRP Ann Manuf Technol 37(2):611–622

## Monitoring Algorithm

► Monitoring

## Monitoring Strategy

► Monitoring

## Monitoring System

► Monitoring

## Motion Control System

► Servo System

## Mounting

► Assembly

## Moving Materials

► Handling

## MSA

► Measurement System Analysis

## Multi-agent System

► Agent Theory

## Multi-process Surface

► Stratified Surface

## Multivalued Logic

► Fuzzy Logic