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Rapid Tooling

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Synonyms

Bridge tooling; Direct tooling; Indirect tooling; Prototype tooling

Definition

The term *Rapid Tooling* has three different but related meanings (Mennig and Stoekhert 2013):

1. Strategies for the fast (or rapid) conception of tools, tool inserts, dies, and molds in the sense of a methodology.
2. All, even nonadditive, manufacturing processes or process chains that support to make tools, tool inserts, dies, and molds faster and cheaper than it was possible with traditional tool making but for a lower production outcome. The term includes all kinds of copying or secondary rapid prototyping processes like vacuum casting.
3. Additive manufacturing of tools, tool inserts, dies, and molds in the sense of direct digital manufacturing.

This entry only deals with *Rapid Tooling* in the sense of direct digital layer-oriented fabrication as defined under bullet point 3.

Rapid Tooling sometimes is misunderstood as automated making of the entire tool. In fact, it delivers complex tool components like conformal cooled inserts or sliders as elements of a series tool.

Theory and Applications

The term *Rapid Tooling* goes back to the early 1990s when rapid prototyping was the collective name for all processes we now call additive manufacturing (AM) (VDI 3405; ISO/ASTM 52900:2015). When the first negatives were made, mainly by inverting the data, they were used as cavities, dies, and molds or mold inserts. To point out the capabilities of this new application of additive manufactured parts, they were called tools, and the procedure was named *Rapid Tooling* accordingly.

The International Academy for Production Engineering et al. (eds.), *CIRP Encyclopedia of Production Engineering*,
https://doi.org/10.1007/978-3-662-53120-4

Introduction

Rapid Tooling is not an automated tool making but a valuable support for a faster, cheaper, and more effective way to better tools. To succeed in Rapid Tooling, a very good match with all nonadditive fabrication steps is needed.

AM is also used to make kernels and molds for sand casting, lost patterns and molds for precision casting, and master models for copying techniques. Tools for lost-wax casting and sand casting are not mentioned as well as copying techniques.

Definition

Additive manufacturing (AM) technology has two application levels: rapid prototyping (RP) and rapid manufacturing (RM) (Fig. 1).

Rapid prototyping means to make parts using RP processes and RP materials. In terms of tooling, it results in Prototype Tooling. In contrast, rapid manufacturing uses materials close to non-AM processing, often named series materials, and results in Direct Tooling (Gebhardt 2006; Gebhardt 2012).

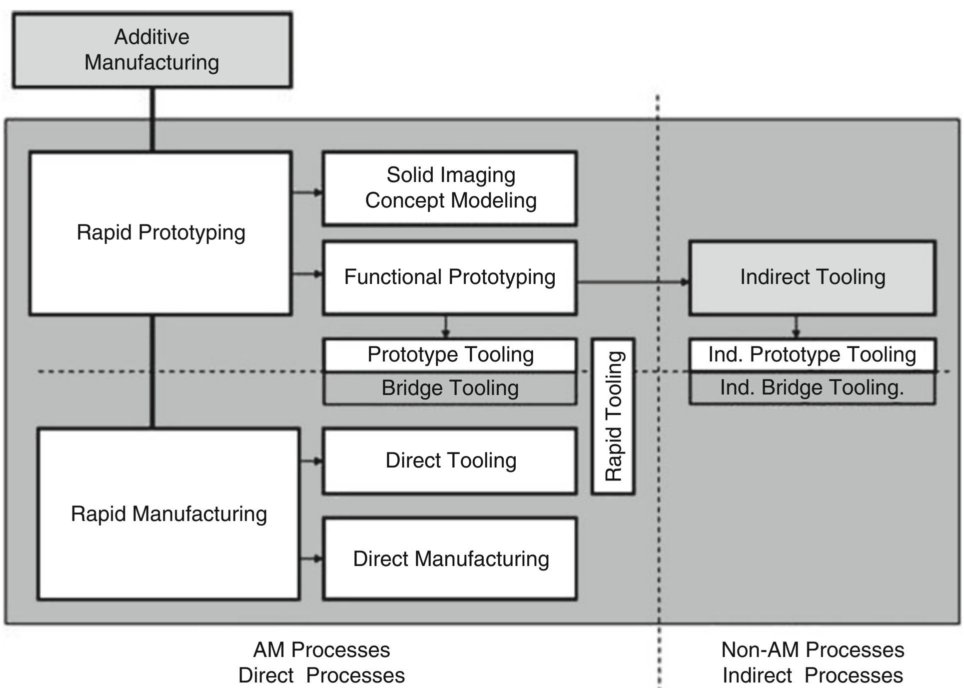
If tools are made by copying rapid prototyping parts or masters, it is called Indirect Tooling, follow-up, or even secondary rapid prototyping, although these are not AM processes.

Tool making by RP processes and materials is called *Bridge Tooling* if the tools can be used to make final products but with limited features like reduced production volume, lower quality, or even similar but different materials. The cons are balanced by the pros like reduced cycle time and costs. The name is based on the idea to bridge the gap between prototype tools and series tools.

Figure 1 underlines that *Rapid Tooling* names a subset of AM but does not define a separate application level.

Additive Manufacturing Processes for Tool Making

The AM principle (Fig. 1) leads to five families, all of them based on the layer technology. They are listed in Table 1 and described in "▶ Additive Manufacturing Technologies." Table 1 contains the generic name, the commercial name (of the



Rapid Tooling, Fig. 1 Structure of the technology of additive manufacturing and its applications: rapid prototyping and rapid manufacturing as well as its correlation with Prototype Tooling, Direct Tooling, and Indirect Tooling

Rapid Tooling, Table 1 The five AM process families. Generic names, commercial names, and its abbreviations

AM process families		
Generic name	Commercial name	Abbr.
1. Polymerization	Stereolithography	(SL)
Polymer printing and jetting		
2. Sintering/melting	(selective) laser sintering	((S)ls)
	Selective laser melting	(SLM)
	Selective mask sintering	(SMS)
Electron beam melting	(EBM)	
3. Layer laminate manufacturing	Layer laminate manufacturing	(LLM)[a]
4. Extrusion	Fused layer modeling	(FLM)[a]
5. 3D printing	Three-dimensional printing	(3DP)

[a]The "M" within the abbreviation stands either for "modeling" or for "manufacturing"

process that mostly is identical with the name of the machine or the manufacturer), and its mostly used abbreviation.

They only differ in the material from which each layer is processed, by the way the contour is made, and by how adjacent layers are bonded.

Some processes need supports that keep the part in shape and stabilize overhangs and interior hollow areas during the generation. Supports have to be added to the part by special (automated) programs and to be removed manually or by special (semi-)automated washing procedures after the build.

To get a deeper understanding of the processes listed above, refer to section "▶ Additive Manufacturing Technologies" listed below. In the following, the AM processes are only mentioned with respect to their capabilities to make tools.

Polymerization

For Prototype Tooling and Indirect Tooling, the precision and very good surface quality of the polymerization is used. Therefore, the parts are preferably used as master models for copying or secondary rapid prototyping processes like vacuum casting, metal spraying, or Course 4 Technology (formerly known as Keltool).

For Direct Tooling the polymerized parts are used as simple tools and tool inserts for low-volume injection casting. 3D Systems introduced the so-called ACES Injection Molding process, AIM (where ACES is a proprietary build style). Except for very soft materials, the molds cannot be used for series production.

The materials used in polymerization processes are photosensitive resins from the acrylate or epoxy type. Since filled materials are available, former disadvantages like limited durability and low thermal resistance have been overcome, and parts can be made even from metals or ceramics.

Actual plastic materials mimic the properties of engineering plastics like polyester, polyamide (even PA 6), ABS, or PEEK.

The advantages of polymerized parts are very good surface quality and fine details. As a disadvantage the supports must be designed prior to and removed after the build, and most processes need post curing.

The machines for polymerization are either from the laser-scanner type (iPro SLA Series, 3D Systems) or use DLP projectors (Perfactory Series, EnvisionTEC), both working with vats. Alternatively polymer printers (MJM, Multi-Jet Modeling Technology) or polymer jetting machines (Eden and Connex Series by Objet/Stratasys or AGILISTA by Keyence) are used that directly print the material on the build platform.

Sintering and Melting

Prototype tools are made directly by sintering of plastics and are used preferably for casting, mainly of soft materials. Because of the rather poor surface quality that requires extensive post-processing, sintered parts, mainly from plastics, are rarely used as masters for Indirect Tooling.

Direct Tooling by sintering and melting of metals can be regarded as the most important process to make tool components to be integrated in the final tools.

Interior channels can be made in a process which puts the idea of contour-adapted conformal cooling into reality.

Generating by laser cladding with a powder nozzle opens up the opportunity of combining different materials in order to optimize the thermal behavior of a tool. The so-called bimetal tools, for example, are made with a built-in copper zone that is applied during the AM process.

Materials for sintering and melting are plastics, metals, or ceramics. Plastics may be unfilled or filled with glass or aluminum spheres or egg-shaped geometries to improve properties like durability and thermal resistance. Also nanoscale particles are used. Unfilled plastics are mostly commodities like semicrystalline polyamides from the PA11 or PA12 type or amorphous plastics like polystyrene (PS). Engineering plastics like PEEK are available.

Ceramics of nearly any type such as Al_2O_3, SiO_2, ZrO_2, and SiC can be processed. Completely sintered parts are made from Si_3N_4. Controlled or graded microstructures, for example, zirconia toughened alumina (ZTA), can be made by depositing a ZrO_2 slurry onto an Al_2O_3 substrate (Gebhardt and Hötter 2016).

Mold halves and kernels can be sintered directly from foundry sands.

Direct Tools are sintered from one- or multi-component metal powders. Today the focus is on one-component powders that allow making parts with properties similar to milling or EDM. Powders are made from steel, mild steel, tool steel, CoCr steel, titanium, and aluminum. The particle size rises from 50 μm down to 20 μm. Small particles require a careful handling, as they may be respirable and explosive. Reactive powders like aluminum and titanium require a completely sealed build space and a closed material handling system flooded with shielding gas.

The mechanical properties of the parts, such as hardness, yield strength, and tension strength, reach almost the values achieved with wrought materials and nonadditive processes.

The greatest advantage of sintering and melting processes is that they can handle all plastic, ceramic, and metal materials that behave like thermoplastics and that are available as powders. Sintering and melting allows to make interior hollow parts. The processes are one-step and do not require supports. The parts can be used directly after the build. Plastic parts require just minor post-processing. The comparably rough surface structure is the biggest disadvantage of the process. Especially, if metal parts are concerned, manually smoothening the surface is laborious and additionally may affect its accuracy.

Laser sintering machines are offered by 3D Systems (Sinterstation sPro SLS Series, HiQ SLS, Pro SLM Series) and EOS (EOSINT P, EOSINT M, EOSINT S), Realizer (SLM 50, SLM 100, SLM 250), SLM Solutions (SLM 125HL, SLM 250HL, SLM 500HL), and Concept Laser (M1 cusing [cusing is an acronym composed from cladding and fusing], M2 cusing, M3 linear, XLine 2000R). Concept Laser and SLM Solutions (SLM, selective laser melting) name their products melting machines. ARCAM's (A1, A2) EBM (EBM, electron beam melting) machine works with an electron beam.

Generating with a powder nozzle is used by Optomec (LENS 705, LENS 800R) and POM (DMD 105D, DMD 44R/66R). Besides this, independent equipment manufacturer design customized machines.

Layer Laminate Processes

Layer laminate manufacturing (LLM) is not frequently used for Prototype and Indirect Tooling. It does not deliver good surface qualities. Fine details should be avoided, as they tend to break. The parts need extensive post-processing. The build process is fast if massive parts are made.

For Direct Tooling LLM results in the so-called lamella tools composed from a set of single layers of some millimeters thickness, joint by ultrasonic welding or mechanically. This rapidly processes massive tools. But they show limited details and need intensive post-processing of its surface. The imprint of the stairsteps can be avoided by covering the tool with deep-throwing foil.

LLM traditionally uses paper or plastics, but metals and ceramics are available as well. As an advantage, LLM processes all types of sheet materials. They are comparably inexpensive. The large amount of waste compensates this favor at least partly. Another disadvantage is the anisotropic mechanical behavior.

Machines that process parts from paper or plastics (PVC) are offered by Cubic Technologies (LOM 1015plus, LOM 2050H, off production), MCOR Technologies (Matrix), Kira (PLT A3–A4, Katana), and Solido (SD300pro).

Fabrisonic (MI, USA) introduced a hybrid milling and ultrasonic welding machine that makes dense aluminum parts based on their so-called ultrasonic consolidation process.

Extrusion Processes

Due to its surface texture and its anisotropic mechanical behavior, extrusion processes are not recommended for tooling, for neither Prototype nor Indirect or Direct Tooling.

Many of the so-called fabbers or printers, which are cheap and easy-to-run personal machines, follow the extrusion principle. The current machines can hardly be used for serious tooling but for making simple patterns. The expected use with carbon-reinforced material or high-performance plastics like PEEK will change the game.

3D Printing (Powder Binder Processes)

Used for Prototype Tooling or Indirect Tooling, 3D printing quickly leads to not very expensive but not very detailed master models. Because of the poor surface quality and its brittleness that requires infiltration, they are not recommended for copying. If nevertheless taken, intensive surface finishing is required.

For Direct Tooling, 3D printing allows making tool inserts that may contain interior channels. Infiltration with bronze increases the thermal conductivity that improves the cycle time if the mechanical properties can be accepted.

3D printing is suitable to process plastics, metals, and ceramics. Standard materials are plaster-based vinyl composites (copolymers) that are used not only for show and tell models but for lost pattern for casting as well (3D Systems/Z-Corp). Voxeljet uses PMMA qualities; ExOne is specialized on sand qualities for sand casting patterns. Metal powders (ExOne) can be mild steel (comparable to X2CrNiMo; 1.4404) or tool steel (X42Cr13; 1.2083). Within the oven process, a hardness of 54 HRC can be achieved. Due to the infiltration with bronze, the thermal conductivity is high, but the mechanical properties of the parts do not reach the level of wrought materials.

As an advantage, 3D printing can handle all materials that are available as powders and can be solidified by binders. No supports are required. The process works at room temperature, thus avoiding thermal distortion. Interior hollow structures can be made. It is disadvantageous that metal processes are multistep procedures that require a subsequent oven process and infiltration with bronze or another low-melting-point metal. The comparably rough surface quality is a disadvantage, too. Metal processes require an intensive post-processing which additionally affects the accuracy.

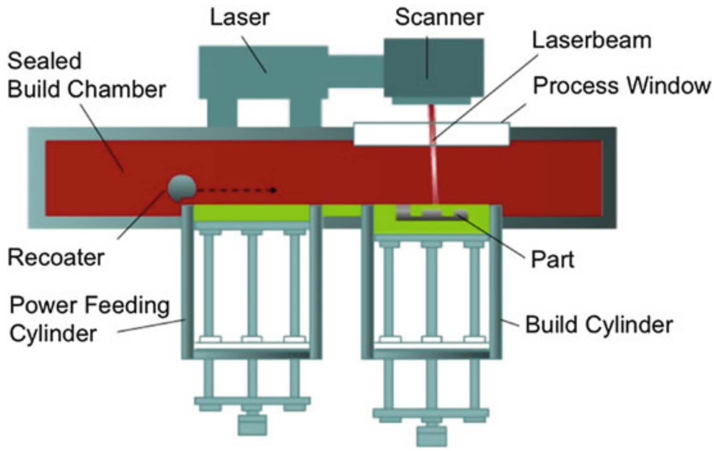
The majority of the 3D printing machines are designed for making plastic-like parts, for example, 3D Systems (Z-Printer 310plus, Z-Printer 350, Z-Printer 450, Z-Printer 650) or Voxeljet (VX800, VX500). ExOne developed a family of metal machines, called *direct metal printers* (M-Flex, M-Print). A *densification furnace* for debinding and supporting infiltration as well as a cleaning station is available.

Machines for Additive Manufacturing: Tooling

A detailed description of AM machines normally is not part of a tooling chapter. But, as machines for AM are less known by a wider audience, at least the basic setup of machines for additive manufacturing will be shown. For a detailed description of particular machines, see Gebhardt and Hoetter (2016).

As pointed out above, sintering and melting is essential for tooling. A sample setup of a laser sintering or melting machine is shown in Fig. 2. The machine is completely sealed and equipped for high-temperature processes that work with shielding gas but shows all elements of an arbitrary laser sintering or melting machine: The laser-scanner unit for contouring each layer, the build area with a movable piston in which contouring and generating take place simultaneously, the powder reservoir, and the powder feeder can be seen clearly.

Figure 3a, b shows two different laser melting machines with sealed build chambers for the



Rapid Tooling, Fig. 2 Laser sintering machine, scheme of a sealed build chamber for high-temperature processing. (According to Phenix, F)

Rapid Tooling, Fig. 3 (**a**) Laser melting machine with sealed build space Realizer SLM 100. (Source: Realizer). (**b**) Laser melting machine Concept Laser M3linear, with exchangeable generating module. (Source: Concept Laser)

processing of reactive materials such as titanium. The machine (Fig. 3b) cannot just do AM but engraving and marking due to exchangeable modules as well.

Samples

Prototype Tooling

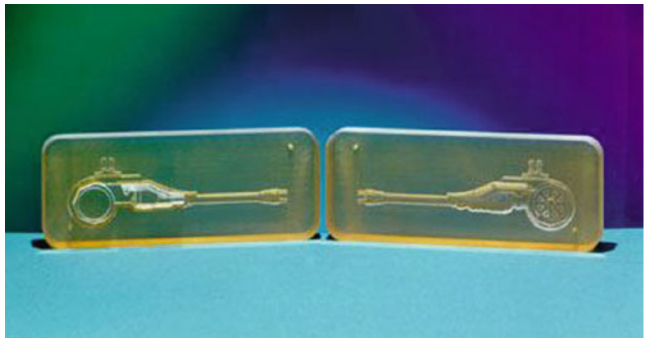
Examples of Prototype Tooling by AM are the directly generated tool insert made by stereolithography (AIM) shown in Fig. 4 that was applied on an injection molding machine and the boot's sole profile (Fig. 5) that was cast manually. Similar tool inserts can be made by using polymer printers (MJM, Multi-Jet Modeling Technology) like the machines made by Stratasys/Objet or Keyence.

Direct Tooling

Direct Tooling preferably is applied to make cavities, sliders, and tool inserts from tool steel. The mostly used process is laser sintering of metals (SLM, selective laser melting) using a powder bed process. Generating with a powder nozzle (DMD, direct metal deposition) is mainly used for repair.

In Fig. 6a–c there are displayed tool inserts obtained from different AM processes. They

Rapid Tooling, Fig. 4 Cavity made by stereolithography (AIM), inserted in a master mold frame. (Source: 3D Systems)



Rapid Tooling, Fig. 5 Sole profile of a rubber boot (EOS direct pattern method) and casted sole. Laser sintering, polyamide. (Source: EOS)

show details like interior channels (or cooling grids) for conformal cooling application, dome-shaped stand-alone structures, or deep and narrow gaps.

AM is very suitable to make exchangeable tool inserts for flexible tool concepts. As an example a tool insert for a cockpit tool can be seen in Fig. 7.

Figure 8 shows a tool insert for a series tool used for high-volume production of toothbrush heads. The left side of the picture shows the part as it comes from the AM process (SLM) including the starter holes for EDM. The right part shows the final part after post-processing by milling and EDM. The part is made by SLM from tool steel (1.2343) with a hardness of HRC 53 (without thermal posttreatment).

A systematical approach to optimize the combination of AM and non-AM process steps while making a tool is evaluated by the EcoMold project. The tool elements are generated directly on the clamping device in order to simplify the final machining of the part and the assembly of the entire tool (Fig. 9).

Examples for the direct application using a powder nozzle and laser for repair and maintenance are the damaged texture on Fig. 10 and the buildup of a tool insert made from 1.2343 on a prefabricated substrate made from the same material.

Figure 11 shows an SLM part as processed (left) and after final machining (right).

AM is also used for the production of standard tool elements like the cooling stick in Fig. 12 that shows a cooling duct with a spiral shaped interior.

Characterization of AM Tooling in Contrast to Non-AM Tooling

Non-AM processes, mainly machining like milling and EDM, dominate tooling. AM is not widely used until now. Therefore, it seems to be helpful to characterize AM processes in contrast to non-AM processes regarding the main aspects like materials, fabrication tools, build strategy, CAD compatibility, accuracy, and amount of manual work.

Materials

Non-AM processes work with a large range of wrought materials that are selected according to the desired part properties (product-oriented material selection).

AM processes work with a comparable small range of materials. Some of them are optimized to meet the AM process requirements first. Therefore, often the desired mechanical properties are only approximated (process-oriented material selection).

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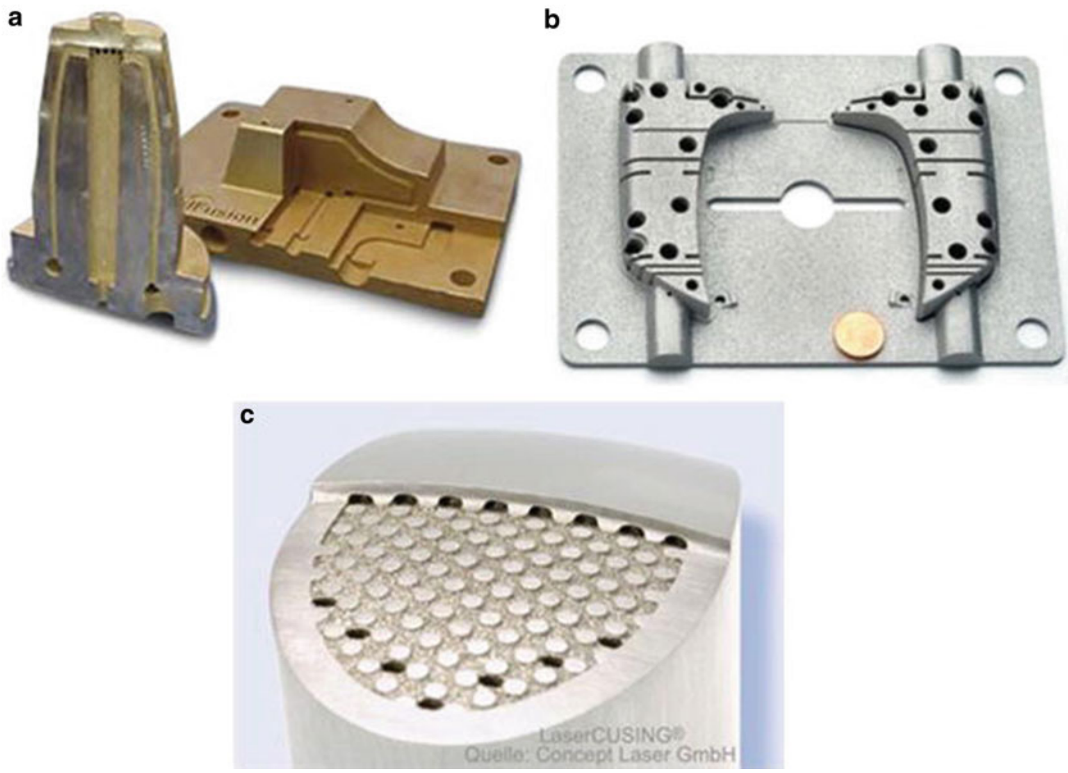
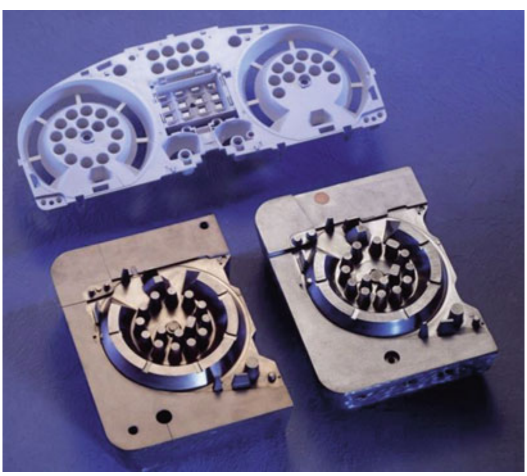


Rapid Tooling, Fig. 6 Tool inserts made by different metal AM processes (partly as a cutaway view): (**a**) Direct metal printing process (Prometal), (**b**) selective laser melting (SLM Solutions), (**c**) LaserCusing (Concept Laser). (Source: Manufacturers)



Rapid Tooling, Fig. 7 Interchangeable tool inserts for a passenger car cockpit and corresponding injection molded part. (Source: EOS)

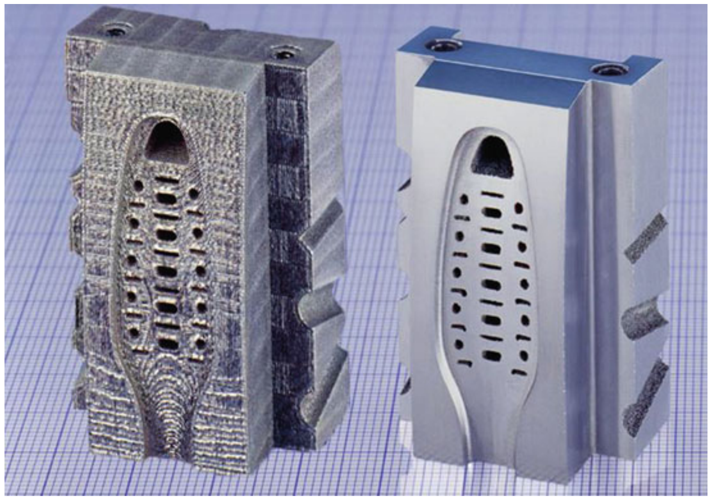
Fabrication Tools

Non-AM processes use a great variety of different tools, optimized for a particular process step. They are changed frequently from one process step to another or even within (product-oriented tool selection).

AM processes work without part-specific tools (tool-less). The tool is represented by the element that contours each layer and joins adjacent layers. It is changed neither during the build process nor from one build process to another (process-oriented tool selection).

Build Strategy

Due to fabrication limits, such as clamping, non-AM parts are mostly assembled or joined from a number of elements that also can be made from different materials (process-oriented build strategy).



Rapid Tooling, Fig. 8 Tool insert for toothbrush heads. As from AM process (*left*); finished part (*right*). (Source: P&G/Braun; Trumpf)

Rapid Tooling, Fig. 9 EcoMold project. Part during AM process (*left*), AM and non-AM manufactured tool elements (*center*), completed half of the tool (*right*). (Source: FhG IFAM, Bremen, D)

Because of the unlimited freedom of geometry, AM parts can be perfectly adapted to its functions. Functions can be integrated into the part, and the part can be built as one piece (product-oriented build strategy).

CAD Compatibility

CAD models for non-AM are transformed to the machine control by different kinds of special programs called (pre)processors. Data sets are machine-specific in the way that most of it only run with the control it was written for. This is called a machine-oriented programming.

AM processes are run using standardized so-called STL (or AMF) data sets. They are derived from the CAD data as well but can be used on any additive manufacturing unit available. If another additive manufacturing machine is used, the program remains unchanged (autonomous or machine-independent programming).

Accuracy

Non-AM machines define the standards.

AM processes show a comparable accuracy mainly for the contour, which means in the build area and thus two dimensionally. Because of the layer principle with even layer thicknesses, making the third dimension causes stair-stepping effects which means additional inaccuracy.

Non-AM processes are known very well. Therefore, usually the maximum accuracy is obtained from the first run even in the daily routine.

AM is about to reach accuracies comparable with non-AM. Additionally AM requires proper calibration. Based on a longer experience,

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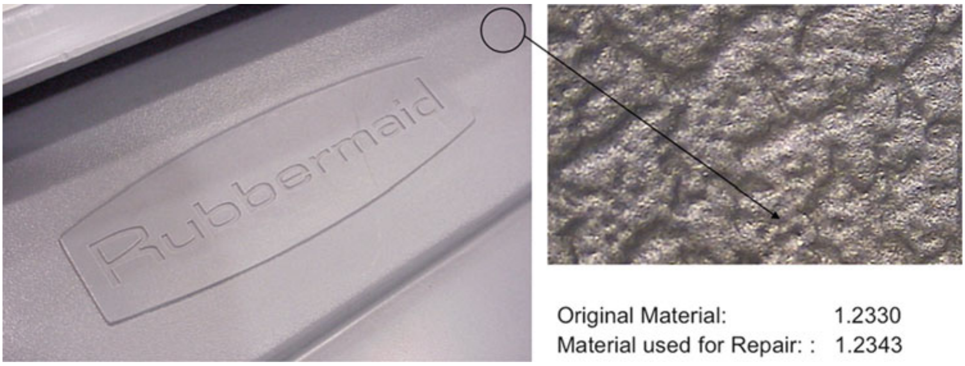
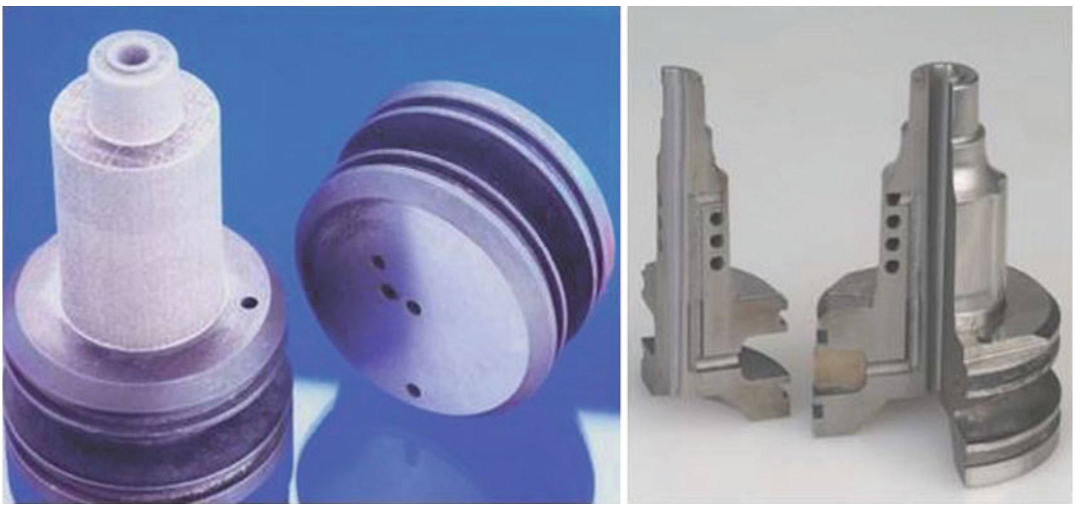


Rapid Tooling, Fig. 10 Repair of a textured surface, laser generating with powder nozzle. (Source: Trumpf)



Rapid Tooling, Fig. 11 Laser generating with powder nozzle. Tool insert, buildup on a prefabricated substrate (often called hybrid process), both made from 1.2343. Part as processed (*left*), after final machining (*right*). (Source: Innoshape)

Rapid Tooling, Fig. 12 AM tool element: cooling stick. Cutaway view (*left*) and final part (*right*). LaserCusing. (Source: Hofmann)

such calibration runs can be reduced to a minimum. Simulation tools are under development in order to reduce it further.

Amount of Manual Work

State-of-the-art non-AM processes like high-speed milling deliver parts that either does not need any post-process machining or just a surface finishing that does not affect its accuracy.

AM processes show stair-stepping effects. Comparably soft materials such as plastics can be easily finished manually. This shows best results but incorporates the risk of geometric distortions, especially if different workers finish the same series of parts. Automated post-processing and finishing processes are under development.

Conclusion

The discussion underlines that non-AM processes are advantageous in terms of accuracy, material properties, reproducibility, and, depending on the complexity of the part, build speed. This is especially true if the part's geometry is simple.

That is why successful use of AM requires complex geometry, short delivery time, and small series or one-offs.

Trends

SLM machines dominate the applications, but Electron Beam equipped machines are coming up especially for tick walled parts.

The SLM machines tend to show bigger build chambers and speed up the process using up to 4 lasers simultaneously.

All nonadditive and additive process steps will be integrated in one machine, increasing both productivity and economy.

Cross-References

▶ Additive Manufacturing Technologies

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Rayleigh-Ritz-Galerkin Methods

▶ Finite Element Method

Reaming

▶ Fine Finishing of Holes

Rebuild

▶ Remanufacturing

Reconditioning

▶ Remanufacturing

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Reconfigurable Manufacturing System

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Synonyms

Changeable manufacturing system

Definition

Reconfigurable manufacturing system (RMS) is one designed at the outset for rapid change in its structure, as well as in its hardware and software components, in order to quickly adjust its production capacity and functionality, within a part family, in response to market changes. A typical large RMS system consists of some 15–150 machines operating in concert, where the operations of each machine depend on previous machines and next machines.

Key terms in the above definition are: (1) The RMS is designed at the outset for future changes in its structure. (2) These changes may either increase the system capacity (i.e., maximum annual production volume), or change the system functionality (i.e., to enable producing different parts). (3) Functionality changes in RMS are limited to be within a part family. (4) The RMS design enables rapid execution of its future changes (in order to minimize the idle time of the system between changes). To enable achieving these unique features, the RMS must have special core characteristics.

RMS Characteristics

The RMS possesses six characteristics (Koren 2006). Three operational characteristics enable upgrading the system to achieve exactly the desired capacity and functionality, and guarantee the required product quality. Three structural characteristics enable achieving the operational characteristics (a) quickly and (b) cost-effectively. When possessing the six RMS characteristics, the RMS can deliver **rapidly** and **economically** exactly the capacity and functionality needed, exactly at the time needed by the market. The cost-effective, timely response to market demand is the essence of RMS.

Operational Characteristics

Scalability – the ability to rapidly upgrade existing production capacity by adding machines (Wang and Koren 2013), buffers, or gantries, or by changing the production capacity of reconfigurable machines within that system (e.g., by adding spindles to a machine to increase its productivity (Spicer et al. 2005).) Deif and ElMaraghy (2006) addressed capacity scalability in RMS based on a control approach.

Convertibility – the ability to easily transform the functionality of existing systems, machines, and controls to suit new production requirements (Maier-Speredelozzi et al. 2003). At the system level, conversion require switching machines. At the machine level, conversion may require, for example, switching spindles on a milling machine (e.g., from low-torque high-speed spindle for aluminum, to high-torque low-speed spindle for titanium). To achieve rapid conversion, the RMS must utilize sensing and control methods that enable quick calibration of the machines after conversion.

Diagnosibility – the ability to automatically read the current state of a system in order to detect and diagnose the root cause of product defects, and subsequently quickly correct operational flaws. As production systems are made more reconfigurable and their layouts are modified more frequently, it becomes essential to rapidly tune (or ramp-up) the newly reconfigured system so that it produces quality parts (Hu 1997). Reconfigurable inspection machines (RIM) are embedded in practical RMS to enables product fault detection (Koren and Katz 2003).

Structural Characteristics

Modularity – the compartmentalization of operational functions and requirements into quantifiable units that can be transacted between alternate production schemes to achieve the most optimal arrangement to fit a given set of needs. In RMS, many components are typically modular (e.g., machines, controls, gantries). Modular components can be easily added to increase capacity, or replaced to better suit the functionality needed to manufacture new products.

Integrability – the ability to integrate modules rapidly and precisely by a set of mechanical, informational, and control interfaces that enable integration and communication. At the system level, the machines are the modules that are integrated via material transport systems (conveyors and gantries) to form a reconfigurable system.

Customization – the ability to adapt the customized flexibility (not general flexibility) of production systems and machines to meet new requirements within a product family. Product family means products that have similar geometric features and shapes, the same level of tolerances, and require the same processes. For example, several types of engine blocks compose a product family. Customization enables to design the system flexibility just around a product or a part family, obtaining thereby customized flexibility, as opposed to the general flexibility of FMS. This characteristic allows a reduction in capital cost (Goyal et al. 2013).

Theory and Application

Background and Need

The surge of globalization in the late 1990s created a fierce competition that is causing abrupt variations in product demand, which makes it harder for manufacturing enterprises to predict the future demand for new products (Koren 2010). Prior to the mid-1990s, high-volume manufacturers, such as automakers, enjoyed stable markets with long product lifetimes, in which products were manufactured using dedicated transfer lines. By contrast, manufacturing companies in the twenty-first century are facing increasingly frequent and unpredictable market changes, including rapid introduction of new products, and frequently varying product demand.

Manufacturing systems are designed with a specific production capacity to fulfill a forecasted demand. Production capacity means the maximum volume of output products that a manufacturing system can produce. The designers of manufacturing systems face a challenge regarding the capacity for new systems: If a new system is designed to produce a smaller throughput than the market will require in the future, a tremendous financial loss in losing market share will take place. And if the new manufacturing system is designed to produce a larger throughput than the actual market will need in the future, then the system will be partially idle. Similarly, the shorter product life cycles in the twenty-first century bring about similar reasoning regarding the system flexibility. Reconfigurable manufacturing systems were invented to respond to these challenges (Koren and Ulsoy 2002), and they may be categorized as a class of changeable manufacturing systems (Wiendahl et al. 2007). Since 1999, modern production systems of high-volume mechanical parts (such as engine blocks and cylinder heads) were built as reconfigurable-flexible systems (Krygier 2005). The scientific foundations, characteristics, and design principles of RMS are outlined in a seminal CIRP keynote paper "Reconfigurable Manufacturing Systems" (Koren et al. 1999), which had an enormous impact on establishing RMS as a new global research discipline.

Value Creation by RMS

Traditionally, manufacturing systems are designed with a specific capacity to fulfill a forecasted demand. The designers of manufacturing systems face a tough dilemma regarding the capacity of new manufacturing systems: If the new system is designed to produce a smaller throughput than the market will require in the future, a tremendous financial loss in losing market share will take place. And if the new manufacturing system is designed to produce a larger throughput than the actual market will need in the future, then the system will be partially idle, which means a considerable loss in capital investment – purchasing, installing, and maintaining machines that are not operating. Therefore, if the investment on the excess capacity could be delayed until the capacity is actually needed to supply a steady real demand, the system lifetime cost can be significantly reduced.

If the enterprise management is convinced at the outset of the design process of a new production system that its throughput upgrading will be possible in a cost-effective and timely manner in the future, it facilitates the managerial decision of building new production plants and new manufacturing systems. Designing new manufacturing systems with a potential of volume scalability is imperative in contributing to the profitability of manufacturing enterprises, and satisfying in a timely manner the society needs for new products. System scalability is therefore a significant system characteristic for both the enterprise management and society (Koren 2013).

Rapid and cost-effective reconfigurability of the output of manufacturing systems is an invaluable feature for the management of manufacturing enterprises. System design for reconfigurability allows the enterprise to build a manufacturing system to supply the current demand, and upgrade its throughput in the future, in a cost-effective manner, to meet possible higher market demand in a timely manner. To possess this capability, the manufacturing system architecture must be designed at the outset for future changes to enable supplying exactly the quantities and the type of products needed by the market.

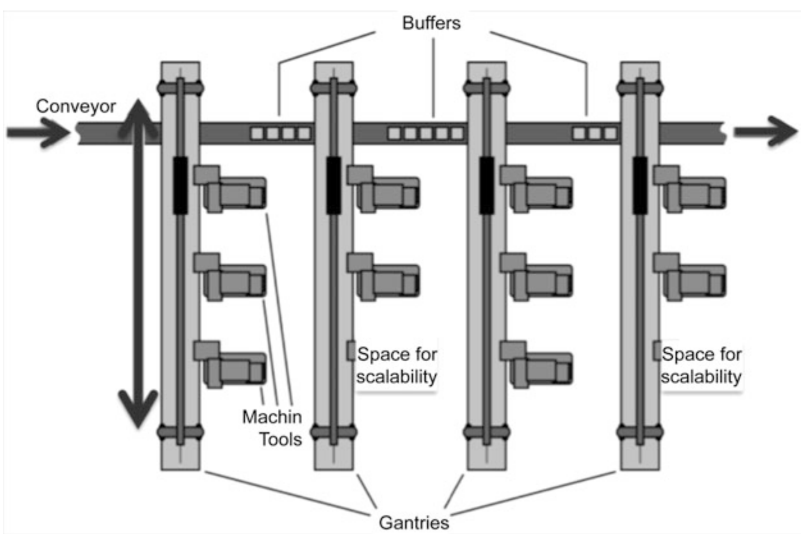
RMS widespread industrial implementations include machining systems (Krygier 2005; Spicer et al. 2002) and assembly systems (Arai et al. 2002; Kong and Ceglarek 2003; Bryan et al. 2013; Gyulai et al. 2014).

System Architecture

A typical reconfigurable manufacturing system consists of several sequential stages, where each stage contains several identical machines that perform exactly the same set of operations. Each part is processed (or inspected) by one machine in each stage. Any machine may process the part in the stage. A sophisticated material transport system (usually consisting of gantries and conveyors) connects the machines to form the system.

A typical RMS architecture is illustrated in Fig. 1. This architecture is composed of many stages (in the auto industry – 5–25 stages) of multiple parallel CNC machines at each stage (usually 3–6), with all machines at a stage performing exactly the same sequence of machining tasks. Each stage has a gantry that loads parts on machines and unloads the machined parts, and moves them to the system part-transfer mechanism (may be a gantry or a conveyor, as shown in Fig. 1). Small buffers (5–10 parts) exist between stages. A part that is processed on a machine in one stage may be transferred to any machine in the next stage. Some researchers refer to this feature as a system with crossovers (Freiheit et al. 2003). Sophisticated selection of optimal RMS configurations takes into account machine failures and machine availability (Youssef and ElMaraghy 2008). Different arrangements and configurations of the machines in the system have a substantial impact on the RMS productivity (Koren et al. 1998; Koren and Shpitalni 2010).

The RMS designer should take into account possible scalability that increases its production volume to match the system output to future market demand. Achieving cost-effective scalability depends on the original system design layout.



Reconfigurable Manufacturing System, Fig. 1 The layout of a typical reconfigurable manufacturing system

A valuable practical approach to scale up the capacity of reconfigurable system is adding CNC machines to existing manufacturing systems. Figure 1 depicts empty spaces reserved for adding future machines if capacity scalability will be needed. These spaces are reserved in strategically calculated places that depend on the product and future market forecast (Wang and Koren 2012). Principles of design for scalability may assist in allocating spaces for additional machines (Wang and Koren 2013). The speed of scaling up the system capacity depends also on the type of the material handling devices. Each time that machines are added, the material handling system must be adapted to serve the new system layout. The RMS designer should be aware that the estimated product life cycle might have an impact on the system configuration (Hon and Xu 2007).

One of the most critical issues in operating efficiently any manufacturing system is the balancing of its operations. System balancing means that each station (e.g., machine, assembly post, etc.) along a production line has almost the same cycle time, so that the idle time when some machines complete their tasks quicker than other machines in the system is minimized. System balancing enables synchronization of the operations and is essential in obtaining high throughput in both assembly and machining systems (Tang et al. 2004). In most cases, adding machines or assembly stations after scalability requires rebalancing of the system operations. System balancing is usually accomplished by shifting operations among machines in the system, but it may be also achieved by scaling the capacity of individual pieces of equipment (Spicer et al. 2005).

A futuristic RMS architecture is illustrated in Fig. 2. In this architecture, a stage may include either CNC machines or reconfigurable machine tools (Landers et al. 2001). The inclusion of RMTs in stages 2 and 4 enhance the system reconfiguration capability. There are reconfigurable systems that include inspection stages, allowing each part to be inspected in real time (Krygier 2005). The system in Fig. 2 includes also reconfigurable inspection machines (Koren and Katz 2003), which facilitate the integration of the RMS diagnosibility characteristic into the RMS. The Return System has two tasks: (1) sending back bad parts that failed in the inspection stages, and (2) in case of machine failures the return conveyor allows system balancing to enhance throughput.

RMS, FMS, and Changeable Manufacturing

Reconfigurable manufacturing systems and flexible manufacturing systems have different goals. The FMS's main goal is to enlarge the variety of parts that can be produced. The RMS aims at increasing the speed of responsiveness to markets and customers. The RMS is also flexible, but only to a limited extent – its flexibility is confined to only that necessary to produce a part family. This is the "customized flexibility" or the customization characteristic, which is not the general flexibility that FMS offers. The advantages of the customized flexibility are faster throughput and

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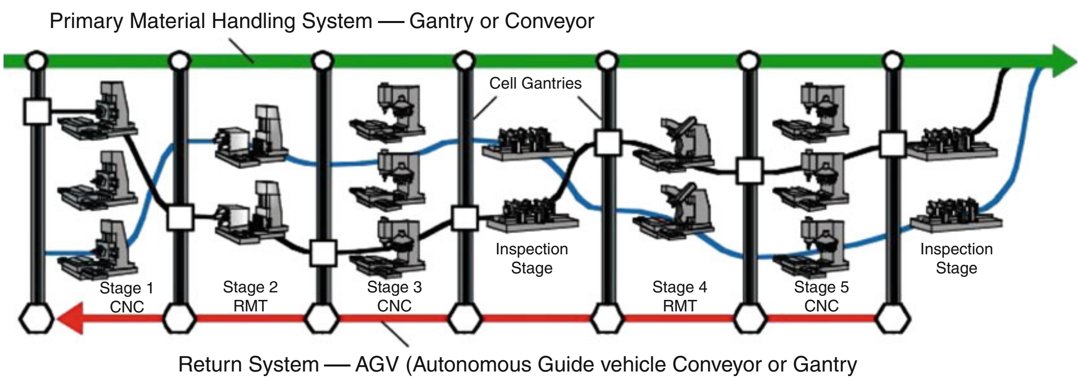

Reconfigurable Manufacturing System, Fig. 2 The layout of a futuristic reconfigurable manufacturing system higher production rates. Therefore, the process planning of RMS is more challenging than that of FMS (Azab and ElMaraghy 2007). Other important advantages of RMS are rapid scalability to the desired volume and convertibility, which are obtained within reasonable cost to manufacturers. The best application of a FMS is found in production of small sets of products. With RMS, however, production volume may vary from small to large. Changeable manufacturing systems are related to RMS. However, changeable manufacturing is broader than RMS and deals also with moving whole factories between locations to adjust production capacity to geographical regions (Wiendahl et al. 2007).

Cross-References

- ▶ Changeable Manufacturing
- ▶ Computer Numerical Control
- ▶ Factory
- ▶ Machine Tool
- ▶ Manufacturing System
- ▶ Production
- ▶ Productivity

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Recycling

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Synonyms

Material recovery

Definition

Recycling is an alternative for the management of an end-of-use product. Recycling is the process of material value recovery and is often undertaken when recovery of functional value (e.g., reuse, refurbishing, or remanufacturing) is not technically or economically feasible.

Extended Definition

Recycling includes the activities of returning a product, components, or material to a processor who then transforms these entities into materials that can be used to create new products. The recycling system often includes such steps as product recovery, transportation, shredding, sorting, and materials processing. With recycling, the original product/component structure is very rarely preserved (Fig. 1).

Theory and Application

Recycling is the set of activities required to recover used products, return them to a processing facility, and process the product/components as needed to produce materials that can be used to create new products. The production of materials via recycling is often referred to as secondary materials processing as opposed to primary materials processing that is focused on working with virgin material resources. Recycling is often motivated by the significant recovered value associated with materials such as steel, aluminum, and copper. These materials are widely recycled due to the availability of reprocessing technologies and the existence of a global demand or markets for recycled materials. Recycling, as with other end-of-use alternatives, is highly influenced by the original design of a product. The application of design for recycling (DfR) seeks to create products that enable or promote recycling, e.g., they

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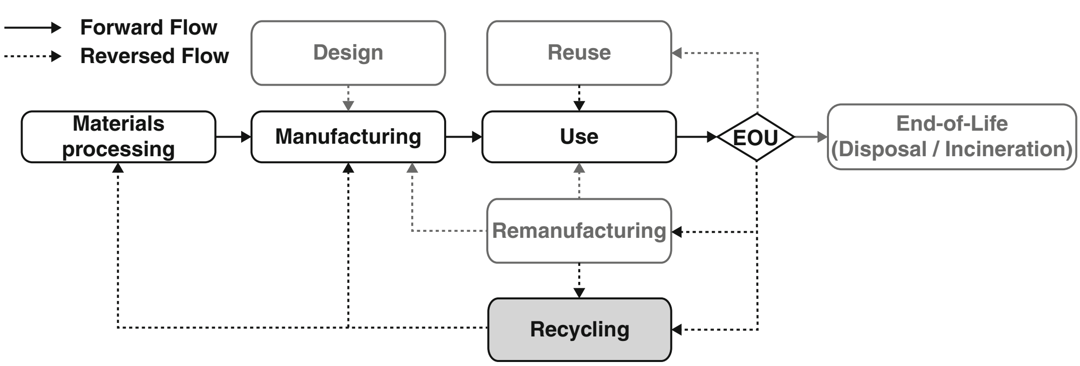

Recycling, Fig. 1 The role of recycling in the product life cycle reduce or eliminate hazardous materials (thus making it easier to process them at end of use), they employ more recycled or low-impact material content, and they have greater modularity that allows easier disassembly (Ardente et al. 2003). The decisions associated with recycling include (i) the best alternatives for recovery of used products, (ii) the best approach for transporting used products, (iii) the most appropriate shredding and sortation technologies, and (iv) innovative strategies for improved processing of recovered materials. There are issues associated with the consumer perception of recycled materials and the management of products that contain hazardous substances (Sjödin et al. 2000; Bi et al. 2007; Rahimifard et al. 2009). Further information on recycling strategy is provided in Pigosso et al. (2010), Rahimifard et al. (2009), and Sasikumar and Kannan (2008).

Recycling, Recyclable, and Upcycling

The existence of a reverse supply chain able to collect, separate, and reprocess materials can make a product *recyclable*. In other words, the materials used in the product might be recovered as a material for an additional use. Once this reverse process is completed – and the used product is converted into a material from which a new product is fabricated – it is said that the product was *recycled. A recycled product* can be made, totally or partially, from recovered materials, and it might have been reprocessed to serve as part of a new or the original product.

The decision about using the recycled material to manufacture a new product or manufacture the original product varies depending on the product purpose and material characteristics. For instance, a detergent plastic bottle might have been made from recycled water bottles; however, the opposite is often not possible due to safety regulations. In the case of glass or metals, the reprocessing treatment involves high temperatures that successfully eliminate all impurities. For this reason, products containing these materials are more suitable for closed-loop recycling to manufacture the original product.

The closed-loop recycling of materials into their original form is sometimes referred to as *upcycling*. This concept is more frequently associated with the ability to continue or perpetuate the recovery of materials into the original supply chain without altering their value. A traditional example is the recycled beverage cans that might be integrated in the same manufacturing process as new cans (McDonough and Braungart 2002). In contrast, open-loop recycling implies that recycled materials are used to manufacture a new product with a different purpose. For example, cardboard can be made from recycled paper or new clothes can be made from recycled fibers.

Secondary Markets for Recycled Materials

The recovering, reprocessing, and reutilization of critical materials such as steel, copper, aluminum, and rare earths are very important to reduce the overall resource consumption rate and mitigate market effects associated with supply shortages. In addition, the economic impact of trading recycled metals and minerals is having a significant impact on the US economy. The US Geological Survey (2012) estimates the quantities produced, traded, consumed, and recycled of various materials in the USA. In the case of steel, for instance, the highest steel recycling rates are obtained from vehicles, appliances, and steel cans. The increased recycling rates have greatly reduced the need to produce virgin steel. Other materials such as copper and aluminum are increasing the production from old scrap obtained from used products and in-process scrap derived from fabricating operations. Copper is mainly recovered from bass mills, foundries, and chemical plants. The recovery of aluminum is mostly due to manufacturing scrap; however, the alloying elements used to produce aluminum alloys (i.e., Mn, Si, Zn, Cu, and Mn) with certain industry specifications have a higher carbon footprint and might complicate the recycling after end of use (Das 2011). In the case of rare earths, the secondary market is emerging and gaining importance due to high prices and demand of these minerals.

Small quantities are recovered from permanent magnets mainly.

According to the European Environment Agency (2011), the contribution of recycling to society is noteworthy for several reasons, e.g., resource efficiency, job generation, and economic benefits. Critical materials such as metals, glass, paper, and plastic are widely traded and their prices are increasing. The employment associated with recycling of these materials has an annual growth of 11%, and this subsector of the economy employed 3.4 million people in 2008. Furthermore, recycling is perceived as a key player in supplying materials for emerging economies, providing opportunities for business creation, and building up infrastructure and markets not explored before.

The Japanese experience in recycling of appliances has also been successful, not only in terms of economics but also in terms of engaging the supply chain actors involved in the recovery process. Customer, retailers, and manufacturers share the responsibility in the recovery and recycling of household appliances. Iron, copper, aluminum, and glass are the main materials recovered from TV sets, air conditioners, refrigerators, and washing machines discarded at the recycling plants every year (MEGJ 2012).

Cross-References

- ▶ EOL Treatment
- ▶ Remanufacturing
- ▶ Reuse

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Reducer Rolling

▶ Forge Rolling

Reengineering

▶ Optimization in Manufacturing Systems, Fundamentals

Reflectance

▶ Reflectivity

Reflection Coefficient

▶ Reflectivity

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Reflectivity

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Synonyms

Reflectance; Reflection coefficient

Definition

Fraction of incoming light that is reflected at an interface.

Theory and Application

The most general definition of a reflection quantity is the bidirectional spectral reflectivity. The relevant angles are defined in Fig. 1, where the surface is in the x-y plane (see Fig. 1, Haitjema 1989):

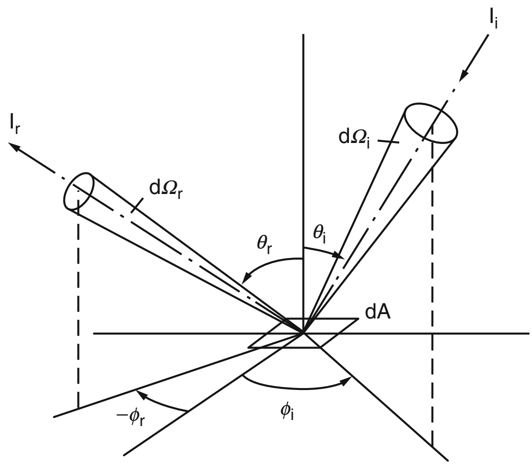
This is expressed in Eq. (1):

$$R(\theta_r, \phi_r, \theta_i, \phi_i, \lambda) = \frac{I_r(\theta_r, \phi_r, \lambda)}{I_i(\theta_i, \phi_i, \lambda)}, \quad (1)$$

where the radiant intensity I_i of the incoming radiation is defined for an infinitesimal wavelength interval $d\lambda$, a surface area dA, and a pencil of solid angle $d\Omega_r$. The *specular spectral reflectivity* is defined as the part of the incoming radiation that is reflected specularly in Eq. 2:

$$R_s(\theta_i, \phi_i, \lambda) = \frac{I_r(\theta_i, \phi_i - \pi, \lambda)}{I_i(\theta_i, \phi_i, \lambda)} \quad (2)$$

This is reduced to the *normal specular spectral reflectance* when the incident radiation is normal to the surface ($\theta_i = 0$ in (2)). The part of the incoming radiation which is reflected from the surface, indifferent in which direction, is called the *directional hemispherical spectral reflectance* and is obtained by integrating the bidirectional spectral reflectance over a hemisphere, see Eq. 3:



Reflectivity, Fig. 1 Parameters used in the definition of bidirectional reflectance

$$R_h(\theta_i, \phi_i, \lambda) = \frac{1}{2\pi} \int_0^{2\pi} \int_0^{\pi} R(\theta_i, \phi_i, \theta_r, \phi_r, \lambda) \sin(\theta_r) \cos(\theta_r) d\theta_r d\phi_r \quad (3)$$

When taking the total intensity of a light source where the intensity over a wavelength interval $d\lambda$ is given by $I(\lambda)d\lambda$, the total directional hemispherical reflectivity is given by Eq. 4 (Siegel and Howell 1972):

$$R_{t,h}(\theta_i, \phi_i) = \frac{\frac{1}{2\pi} \int_\lambda \int_0^{2\pi} \int_0^{\pi} I(\lambda) \cdot R(\theta_i, \phi_i, \theta_r, \phi_r, \lambda) \sin(\theta_r) \cos(\theta_r) d\theta_r d\phi_r d\lambda}{\int_\lambda I(\lambda) d\lambda} \quad (4)$$

This is what is normally considered as "reflectivity."

Reflectivity at a Plane Interface

If an interface is mathematically flat, the reflectivity at that interface can well be described using Fresnel coefficients. The "mathematically" flat implies that the flatness deviations are negligible compared to the wavelength of the reflected radiation involved and that the area considered is much larger than the beam size of the radiation. If these conditions are met, the interface will be specularly reflecting (see Eq. 2).

If the complex refractive index of this flat surface is given by $\boldsymbol{n} = n\text{-}ik$, and the light propagates in air ($n_{\text{air}} \approx 1$), the normal specular reflectivity is given by Eq. 5 (Heavens 1990):

$$R_{\perp}(\lambda) = \frac{(n(\lambda) - 1)^2 + k^2(\lambda)}{(n(\lambda) + 1)^2 + k^2(\lambda)} \quad (5)$$

If the light enters under an angle, the reflectivity will depend on the polarization state of the radiation. The measurement of this polarization state can be used to derive conclusions about the refractive index of this material and even about thin films present. This is called ellipsometry.

Reflectivity at Stratified Planar Structures

The reflectivity at stratified planar structures becomes more complicated if thin film structures are present. Still methods are available to make a straightforward calculation of the reflectivity. For thin film structures, a matrix method has been developed that still gives an analytical solution for the calculated reflectance (Azzam and Bashara 1977; Jackson 1998).

Reflectivity at a Rough Surface

A rough surface will give a more diffuse reflection. For a general calculation, the Maxwell equations need to be solved for the geometry that is extremely tedious. With some approximation, the reflectance can be calculated for periodic profiles or for rather smooth surfaces where the roughness is much smaller than the wavelengths involved. This is further treated by Ogilvy (1991).

Cross-References

▶ Ellipsometry
▶ Roughness
▶ Surface Texture

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Reflectometry

▶ Scatterometry

Reform

▶ Optimization in Manufacturing Systems, Fundamentals

Refurbishing

▶ Remanufacturing

Reliability Test

▶ Durability Test

Remanufacturing

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Synonyms

Overhaul; Rebuild; Reconditioning; Refurbishing

Definition

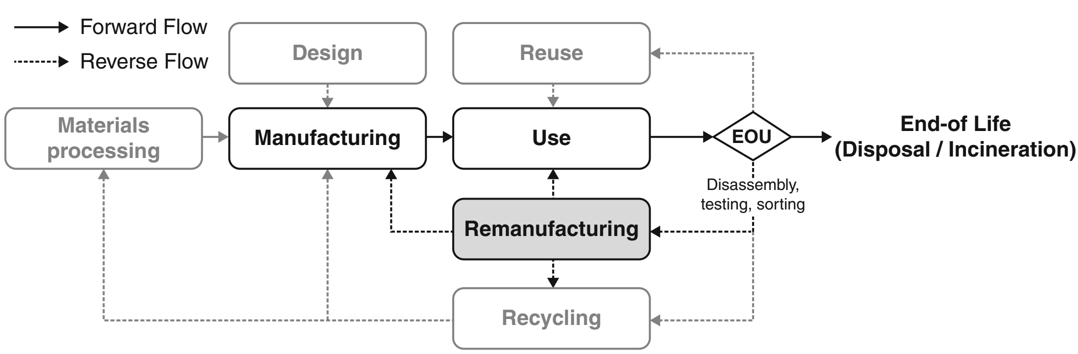
Remanufacturing is a product end-of-use alternative. Remanufacturing is the process of returning a used product (nonfunctional, discarded, or traded in) to at least the original product performance specification.

Extended Definition

Remanufacturing seeks to preserve the functional value added during the design and manufacturing stages of a product life cycle. Although refurbishing is the process of returning a used product to a functional condition or level of performance that is not necessarily equal to the original product specifications, this term is frequently misinterpreted with the remanufacturing concept. When a degraded component cannot be remanufactured successfully or economically, the degraded component is replaced with a new component. Remanufacturing differs from recycling in that it recovers both the material value and the functional value of a used product (Fig. 1).

Theory and Application

In the USA, remanufacturing is a $53 billion industry (Rubio and Corominas 2008). There are over 73,000 companies engaged in remanufacturing that employ 350,000 people in the USA (Behret and Korugan 2005). According to Hauser and Lund (2008), tires (601 plants), motors and engines (382 plants), and vehicle parts (337 plants) are the most significant remanufacturing industries in the USA. In addition to profit, other motivations that push a company to remanufacture their products include a high demand for spare parts during the warranty period, brand protection from independent operators, and unacceptably long lead time for new components (Seitz 2007). However, there is also evidence that remanufacturing provides environmental benefits. Several industry sectors have reported energy savings (e.g., automotive 68–83%, tires 66–68%, appliances 14–44%) and



Remanufacturing, Fig. 1 Remanufacturing as an alternative within the product life cycle

CO_2 emission reductions (e.g., automotive 73–87% and photocopiers 23%). Moreover, relative to the cost of producing new products, remanufacturing can offer cost savings of 50% (Kerr and Ryan 2001; Seitz and Wells 2006; Sutherland et al. 2008; Boustani et al. 2010a, b). Although the reverse logistics of remanufactured products might vary according to product's characteristics, in general, the reverse logistics of remanufactured products includes the following phases:

1. Collection of the used product
2. Sorting
3. Testing
4. Disassembly
5. Cleaning
6. Reprocessing and part replacement
7. Reassembly
8. Inspection
9. Packaging and transportation
10. Re-commercialization

Remanufacturing Challenges

Recognized remanufacturing challenges include the procurement of used products, management of core inventory, quality of returned cores, product disassembly, processing/remanufacturing of components, assembly of remanufactured components, quality of remanufactured products, and appropriate pricing of remanufactured products.

The **procurement of used products** is a critical issue when doing remanufacturing. Firstly, the size, location, and number of facilities as well as the network distribution (centralized or decentralized) might impact the unit cost of remanufactured products. When selecting the facility size for remanufacturing, issues like transportation cost, product yield, and remanufacturing efficiency must be carefully analyzed (Sutherland et al. 2010). Secondly, retailers engaged in the distribution network can serve as collection points for the reverse logistics and facilitate the return process from customers. Lastly, to ensure timely returns of used cores, it is important to create mechanisms to encourage customers to return used cores. Thus, deposits at the time of purchase time, discounts in new products, coupons, leasing alternatives, and service contracts are some examples of common strategies (Östlin et al. 2009).

The **inventory management of core** components faces two concerns, the mismatch between supply and demand of components and the technological obsolescence of the product. Even though good estimates can be made about return rates, these estimates not necessarily work in the practice due to the variability in customer timing of returning a used product. On the other hand, actual return rates added to low inventory turnover could lead to product degradation and obsolescence. Product degradation and technological gap might affect the suitability for remanufacturing.

The **disassembly and reprocessing** is always a multistage process. The inspection made at the time of disassembly has a significant impact on the subsequent reprocessing activities. Only after the product is fully disassembled and the quality of the returned components is determined, the final remanufacturing effort, time, and cost can be estimated. The delays in these stages usually impact the forward commercialization process. The design for disassembly and identification of components since the design phase might facilitate the remanufacturing process as well as avoid additional costs.

The quality of the remanufactured product is paramount to facilitate the integration in the market. The perception of low quality associated with remanufactured products must be overcome in order to make remanufacturing business profitable. In this sense, the traceability of the original product during the use phase, the performance testing after reassembly, the certification of the remanufacturing process, and an equivalent warranty period play a key role in breaking this perception and increasing the confidence of customers in remanufactured products.

Lastly, the **pricing** of remanufactured products has become a subject of debate. Traditionally, remanufactured products have been priced at a lower value than new products due to the reused components. For instance, Siemens remanufactured imaging systems price runs about two-thirds that of a new unit, which are usually priced between $160,000 and $170,000. However, it is still in discussion whether remanufactured products should receive a lower valuation. A diversity of variables such as certification of the final product, number of parts replaced or upgraded, and demand for remanufactured components must be taken into account in this decision.

Economics of Remanufacturing

Recognized companies have been successful in the practice of remanufacturing around the world, namely, Caterpillar remanufacturing engines and gearboxes, Xerox remanufacturing photocopiers, and Siemens remanufacturing cameras and medical devices. The most important benefits are derived from savings due to reductions in the cost of materials and revenues of remanufactured product in new markets. For instance, in 2005, Caterpillar had about $1.5 billion in annual remanufacturing revenue of engines and other components. Even though remanufacturing brings important savings derived from the reduction in the cost of materials, the cost of remanufacturing is volatile because it depends on the quality of the returned product as well as the type of product and industry. In the case of appliances, the highest cost is due to storage (24% approx.), in the automotive industry is due to new part replacement (43% approx.), in the case of mechanical units is due to the cleaning and reconditioning process (50% approx.), and in the electronics case is mainly due to the disassembly and assembly process (80% approx.). In general, the remanufacturing cost is given by

$$RC = A + R_p + R_n + H + D$$

where RC is the total remanufacturing cost, A is the acquisition cost of used cores, R_p is the cost of replaced components, R_n is the reconditioning cost, H is the cost of holding inventory either of used core components or remanufactured products, and D is the disposal cost of materials and components during the remanufacturing process.

Cross-References

▶ Recycling
▶ Reuse

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Reorganization

▶ Optimization in Manufacturing Systems, Fundamentals

Repeatability

▶ Precision

Reprocess

► Reuse

Requirement Specification

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Synonyms

Constraints; Demands; Functional specifications; Technical specifications

Definition

In the (mechanical) design process, the requirement specification is a formal registration of the conditions that are imposed on a new or altered product design, both preceding as well as during the corresponding product development cycle.

Theory and Application

In product development cycles, stakeholders constantly deliberate about alternative solutions to design problems. This observation stresses the importance of decision-making processes for the overall effectiveness and efficiency. Requirement specifications serve as a reference for judging the available decision alternatives. As such, they have a large impact on the course of development cycles (Gottesdiener 2009).

In engineering, a requirement is a singular documented need of what a particular product or service should be or perform. It is most commonly used in a formal sense in systems engineering, software engineering, or enterprise engineering. It is a statement that identifies a necessary attribute, capability, characteristic, or quality of a system in order for it to have value and utility to a user.

In the classical engineering approach, sets of requirements are used as inputs into the design stages of product development. Requirements are also an important input into the verification process, since tests should trace back to specific requirements. Requirements show what elements and functions are necessary for the particular project.

The requirement development phase may have been preceded by a feasibility study or a conceptual analysis phase of the project. The requirement phase may be broken down into requirement elicitation (gathering, understanding, reviewing, and articulating the needs of the stakeholders), analysis (checking for consistency and completeness), specification (documenting the requirements), and validation (making sure the specified requirements are correct).

Product development comprises of the processes that transform the needs of the customer or the marketplace into a product that satisfies these needs. In general, it is a process conducted by designers and engineers, involving many other stakeholders. Although the composition of such product development teams may seem rather intangible, usually there are clear (though possibly implicit) motives to bring together the expertise and domain knowledge of the people involved. Within the context of the organization, the customer (type), the type of product to be developed, and the development team can address the specified need by means of an agreed upon design method.

When decisions are considered instigators of the development process, the nature of the available context for taking a decision becomes increasingly important. The requirement specification can serve as a frame of reference through the entire development cycle and as such is an indispensable part of that context. Throughout the development cycle, the subject of the decisions will change with respect to level of detail, level of aggregation, considered domains, etc. To support a well-substantiated decision, the expression of the requirement specification must ally with the characteristics of the decision at hand. As a structure for the alliance, three types of requirement specification can be discerned: technical specifications, functional specifications, and scenario-based specifications (Lutters and Ten Klooster 2008).

Stated Purpose

All specification types comply with the stated purpose of the development process, which is a predefined, formalized, and static reference of that development process. Therefore, the stated purpose reflects the pre-imposed requirements of (external) stakeholders, like law, marketing, and safety. Due to its static nature, this type of reference hardly influences the selection and use of the different requirement types.

Specification Types

Technical Specifications

Technical specifications are complete and unequivocal expressions of product requirements. They address, e.g., the minimum wall thickness of a beer bottle, the power to weight ratio of a motorcycle, or the nominal size plus tolerance of a shaft in a subassembly. In general, technical specifications express quantitative or easily quantifiable demands.

Functional Specifications

Functional specifications provide a description of desired future product behavior. In general, they express concrete demands to abstract product models. As an example of functional specifications, consider a beer bottle falling of a table. The bottle is required to stay intact after the fall.

Scenario-Based Specifications

In product specifications based on scenarios, emphasis is being placed on the product's environment and the interaction between product and its environment. Product behavior is indicated in terms of what the environment, e.g., the user, can do with a product and how it will interact as opposed to technical or functional specifications where, traditionally, focus is placed on what the product will do and how it does it (Miedema et al. 2007).

Compound Requirement Specification

The solution space in which product development processes are allowed to take place is determined by the frame of reference. The specifications constituting the frame serve as an argumentation and negotiation basis for taking design decisions. In many cases, the specifications will be clear and unambiguous. However, especially in the early stages of a development trajectory, they can be uncertain, incomplete, and even contradicting. In order not to introduce feint certainties in the process, it is important to adequately represent specifications applicable to a certain decision.

Dynamic Requirement Specification

When the frame of reference is constituted by evolving requirement specifications, the relations between the specifications must be dynamic as well. The product definition will concurrently evolve on different levels of aggregation, instigated by different viewpoints, and with respect to different aspects. For the requirement specification to serve as a reference in the entire solution space, it must therefore be possible to interrelate the information constituting the different specification types.

Application

In the (mechanical) design process, the requirement specification is a formal registration of the conditions that are imposed on a new or altered product design, both preceding and during the corresponding product development cycle. For a long time, the use of technical specifications has prevailed in the establishment of such requirement specifications. However, gradually, there is an appreciation for the fact that sheer technical specifications may inadvertently fix constraints and possibilities too early in the process. Moreover, it is recognized that technical specifications are unsuitable to adequately address the role of unquantifiable aspects that play important roles in the development cycle. Using functional specifications and scenarios may aid in addressing these problems.

Application in Development Cycles

In development cycles, two types of phases can be distinguished: diverging and converging phases.

Due to their different natures, the phases require different support methods to establish increased process effectiveness and efficiency.

In diverging phases, adequate support facilitates the generation and evaluation of explicit product information from abstract ideas. A dedicated work environment for performing product development tasks can offer such support by assessing a design in different contexts. These environments are called synthetic environments. In synthetic environments, the use of a.o. media and virtual reality techniques triggers the use of the associative capacities of the stakeholders involved in the performance of the task. They therefore allow development activities based on aggregate influence factors.

For this support to be beneficial to the effectiveness and efficiency of the design process, the synthetic environments must use an explicit but not necessarily decomposed representation of the requirements for reflecting new ideas within the boundaries of the stated purpose. In a synthetic environment, technical and functional requirements are not enough to attain oversight in the early phases. They also do not give much insight in the interrelations and reasons for existence of certain requirements. Typically, scenario-based requirement specifications therefore have the added value to let stakeholders, regardless of their disciplinary background, experience the aggregated quality of their ideas.

In later stages of the development cycle, the divergent product information must be combined in one coherent product model. This process generally requires much iteration; the many, often conflicting, product properties must be brought in harmony, but a change in one aspect induces consequences for the validity of the model with respect to another aspect. In the so-called what-if design method, these relations are modeled explicitly. This allows an automatically generated overview of the possible consequences of a design change. A condition for this type of support to be implemented is that the functional and technical specifications within which changes are allowed are modeled adequately. Moreover, in order to warrant the significance of the product model for the stated purpose of the development process, the modeling must be in harmony with the more general picture of the requirements as agreed upon in previous stages of the design process. This observation stresses the importance of a coherent frame of reference for the entire design process that can be viewed from different perspectives, depending on the need for a specific representation.

Cross-References

▶ Product Development
▶ Virtual Reality
▶ "What-If" Design

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Residual Stress (Abrasive Processes)

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Definition

According to Macherauch et al. (1973), "residual stresses are rigidly effective, multiaxial stresses in a solid system that remain without external forces and moments and are in a mechanical equilibrium." This means that residual stresses are pure internal stresses of a workpiece or a part component. Furthermore, changes in the residual stress distribution are always combined with changes of the part because a new mechanical equilibrium is established after a disturbance of the initial equilibrium.

Theory and Application

Introduction

Residual stresses can be distinguished in macrostresses (Type I) and microstresses (Types II + III) which are characterized by the scale at which they exist within a material. Macrostresses occur over long distances within a material, whereas microstresses exist only locally between workpiece grains or inside a grain (Macherauch et al. 1973).

Type I stresses: Macrostresses are almost homogenous over large distances that involve many workpiece grains.

Type II stresses: These microstresses are almost homogenous over small distances that involve one grain of the material. They can be caused by differences in the microstructure of a material.

Type III stresses: These microstresses are inhomogeneous and exist inside a grain of the material as a result of crystal imperfections within the grain.

Abrasive processes are generally the final process operation in a process chain and determine significantly the functional surface properties of the machined workpiece. Therefore, the properties of the surface layer generated by abrasive processes directly affect the functional properties of the workpiece such as fatigue strength, wear behavior, and chemical resistance (Jawahir et al. 2011). Tensile residual stresses impair mechanical strength properties of a workpiece, whereas compressive tensile stresses have a beneficial effect.

Abrasive processes inevitably lead to changes in residual stresses in both the surface layer and the bulk material. These changes in residual stresses are associated with form changes (distortion). Due to the impact on surface layer characteristics and on part precision, residual stresses play an important role in the manufacture and performance of the machined workpiece (Brinksmeier 1982; Brinksmeier et al. 1982).

Material removal processes, such as abrasive processes, take effect on the residual stresses in two ways. Generally, material volume exposed to residual stresses is removed so that a new mechanical equilibrium establishes. This leads to form changes and a new residual stress state. The second way is the generation of residual stresses by local plastic deformation (creation of stress sources) which disturb the initial equilibrium and consequently also lead to form changes and a new residual stress distribution.

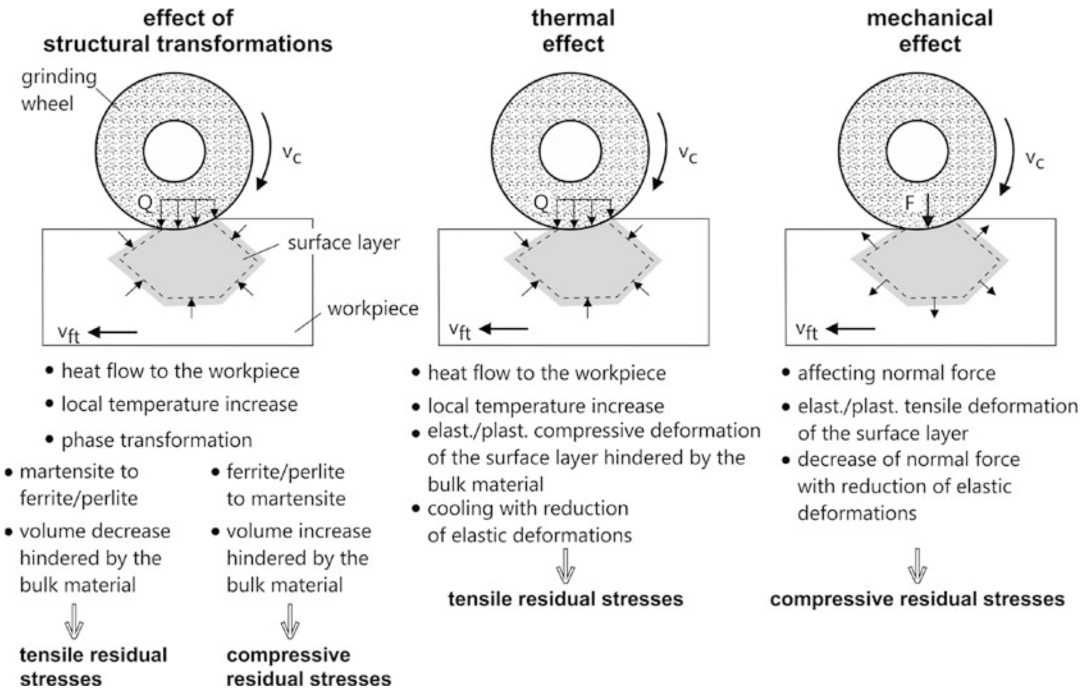
Origin of Residual Stresses in Machining

For understanding the origin of residual stresses, it is necessary to consider the chip removal mechanism in abrasive processes. The chip formation theory is based on the observation of a single cutting grain. The theoretical considerations for the single grain-workpiece interaction in the microscopic scale distinguish between the fields of elastic deformation, elastic and plastic deformation, and elastic and plastic deformation with chip removal (Klocke 2009).

The cutting grain penetrates on a relatively flat path into the workpiece and, after a period of elastic deformation (I), plastic flow of the material (II) occurs. The plastic flow is associated with the formation of lateral bulging. The phase of the actual chip formation (III) begins after reaching a critical chip thickness or depth of cut. The elastic deformation and the plastic flow processes occur in parallel with the chip removal; therefore, the effectiveness of the material removal (and, in turn, the intensity of plastic flow) depends on other factors including the cutting grain geometry, the entry angle of the grain into the workpiece surface, the relative speed of the grain, as well as the friction conditions and the flow properties of the material (Klocke 2009).

Mechanisms for Residual Stress Formation in Abrasive Processes

According to Fig. 1, residual stresses are induced mechanically, thermally, and by



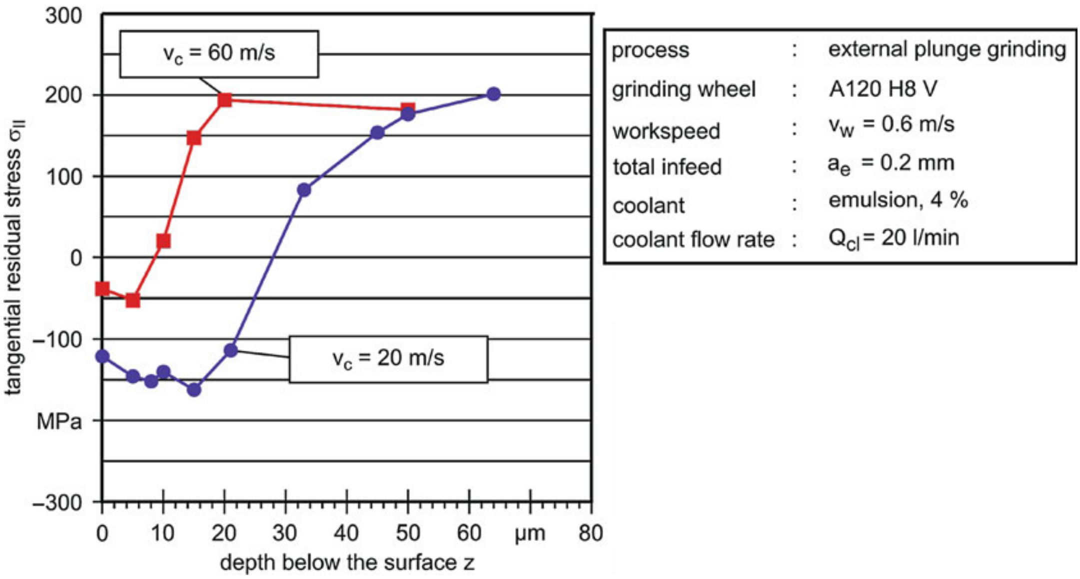
Residual Stress (Abrasive Processes), Fig. 1 Mechanisms of residual stress formation (After Brockhoff and Brinksmeier 1999, with permission from Elsevier)

phase transformation (Brockhoff and Brinksmeier 1999). Each of these impact types can affect the degree of in-process distortion. The residual stress state of the finish parts results from the superposition of thermal and mechanical stresses.

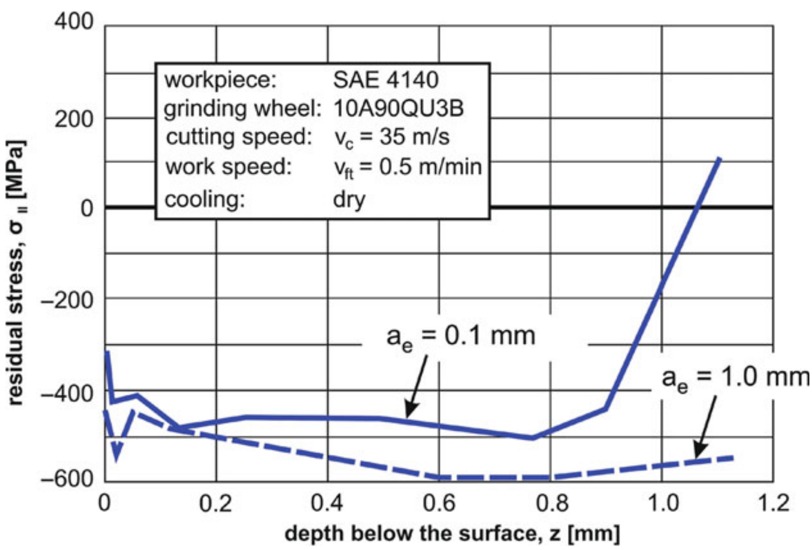
Due to the shearing, cutting, and rubbing processes in Grinding, a lot of heat dissipates through the workpiece surface, which may cause locally high temperatures. The high temperatures in the surface layer and the lower temperatures in the bulk of the workpiece cause an elastic–plastic compression of the surface layer. By cooling the surface layer and the associated recovery of the elastic deformation, tensile residual stresses remain in subsurface. The degree of the thermal stress depends widely on the process temperature, thus on the process parameters, abrasive tool, workpiece material, and coolant. Lower grinding temperatures lead to reduction or elimination of tensile residual stresses in the workpiece surface layer, which is shown exemplarily in Balart et al. (2004).

A mechanical interaction of the abrasive grains with the workpiece usually leads to compressive residual stresses by localized elastic deformation and plastic flow. The predominance of mechanical process effects can be achieved by chip formation with increased ratio of microplowing. This usually occurs in grinding with small chip thickness and low cutting speeds (Fig. 2).

Grinding of hardened steels may cause a phase transformation due to the locally high temperatures in the surface layer. The phase transformation from martensite to ferrite/perlite causes a volume decrease in the surface layer. The volume decrease is hindered by the bulk material, which leads to tensile residual stresses in the surface layer of the workpiece. In contrast to this, grinding of ferritic-pearlitic heat-treatable steel can result in a phase transformation to martensite (grind hardening), and the volume in the surface layer increases (Brockhoff and Brinksmeier 1999). Also the volume increase is hindered by the bulk material whereby compressive stresses in the surface layer occur (Fig. 3).



Residual Stress (Abrasive Processes), Fig. 2 Residual stress profile at different process conditions after grinding with work-hardening effect (After Heinzel and Bleil 2007, with permission from Elsevier)



Residual Stress (Abrasive Processes), Fig. 3 Residual stress profile at different process conditions resultant from transformation of ferritic-pearlitic to martensite phase after grind hardening (After Brockhoff and Brinksmeier 1999, with permission from Elsevier)

Cross-References

- ▶ Chip Formation (Abrasive Process)
- ▶ Grinding
- ▶ Grinding Fluids
- ▶ Grinding Burn
- ▶ Wear Mechanisms

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Residual Stress (Forming)

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Definition

Residual stress is the stress field inside a material that has been subjected to permanent deformation beyond its limit of plasticity or remaining elastic stresses in a workpiece, e.g., due to non-uniform plastic deformation and/or significant temperature gradients.

Theory and Application

Introduction

If the plastic deformation is uniaxial, such as that induced in a tensile test, and the material is isotropic without the initial stress field, the stress of a permanently strained material can recover to its initial state without residual stress. The stress–strain curve in Fig. 1 explains elastic recovery in such a case. The material after uniaxial tensile deformation can fully recover after unloading the imposed external force, because its stress is uniform without a gradient, and it can deform freely in the opposite direction to that of loading. However, in general, every point in a material after loading or forming has a stress gradient and cannot deform freely during unloading to recover the stress field. Thus, the stress at every point in a material causes some of the stress before unloading or the stress state during forming to remain. This is the cause of residual stress, and it is closely related to elastic recovery. Residual stress is affected by the ease or difficulty of elastic deformation during unloading or elastic recovery; therefore, the residual stress at every point in a material is affected by the surrounding points, which limit deformation during unloading, while perfect elastic recovery without any constraints on deformation during unloading will result in zero residual stress. In summary, the amount of residual stress depends on the magnitude of the final stress and also on various factors influencing the constraints on deformation during unloading such as the stiffness of the material.

Description of Residual Stress

A material undergoing forming can be modeled as a deforming body under external force T with boundary S_f and constrained displacement U with boundary S_u, as illustrated in Fig. 2. The stress $\boldsymbol{\sigma}$ at every point in a deforming body should obey the following equilibrium equation or momentum equation:

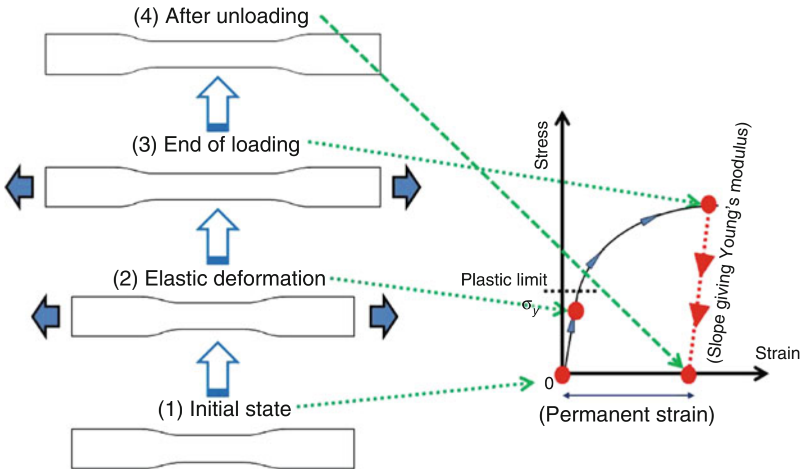
$$\mathbf{a} = \rho^{-1}\mathrm{div}\ \sigma(\mathbf{r}), \tag{1}$$

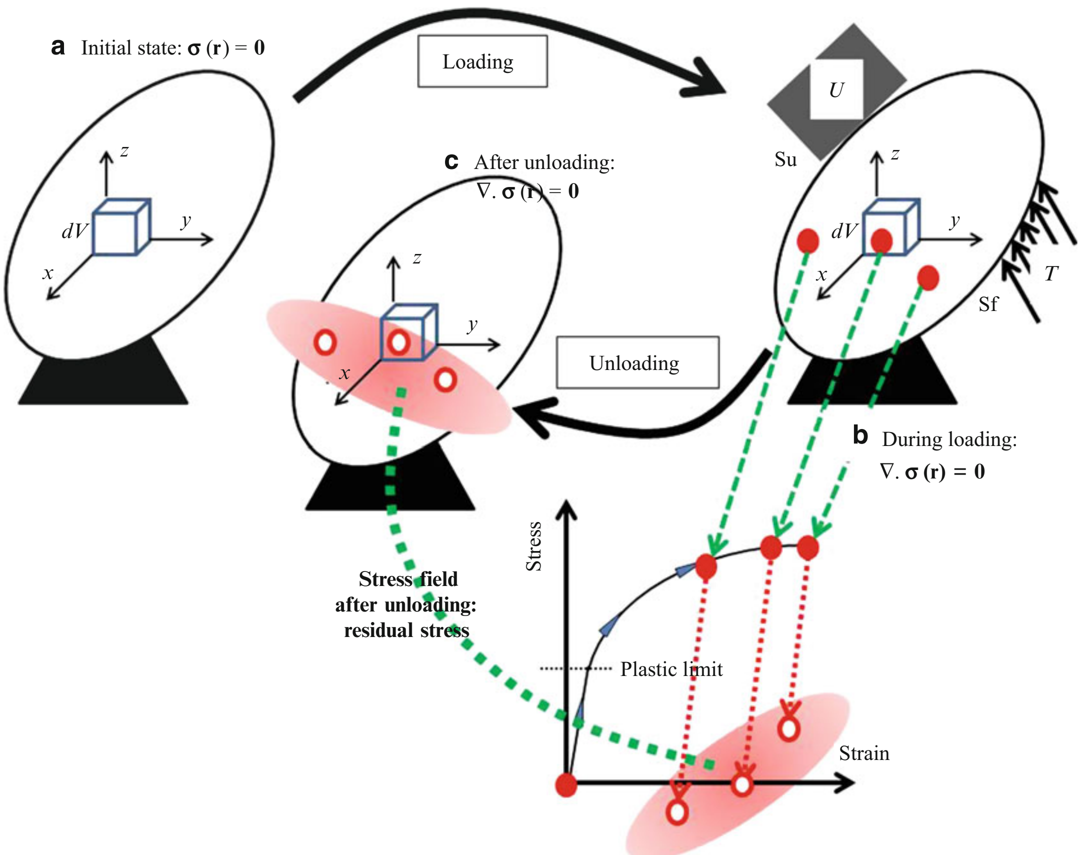
where $\mathbf{a}$ is acceleration, $\mathbf{r}$ is a position vector, and ρ is density. Generally, acceleration is negligibly small compared with the divergence of stress in forming; thus, momentum Eq. 1 yields the static equilibrium condition given by Eq. 2:

$$\mathrm{div}\sigma(\mathbf{r}) = \mathbf{0}. \tag{2}$$

If the material has not been strained beyond the limit of plasticity, the stress field of the material recovers to the initial state when the external force and boundary displacement

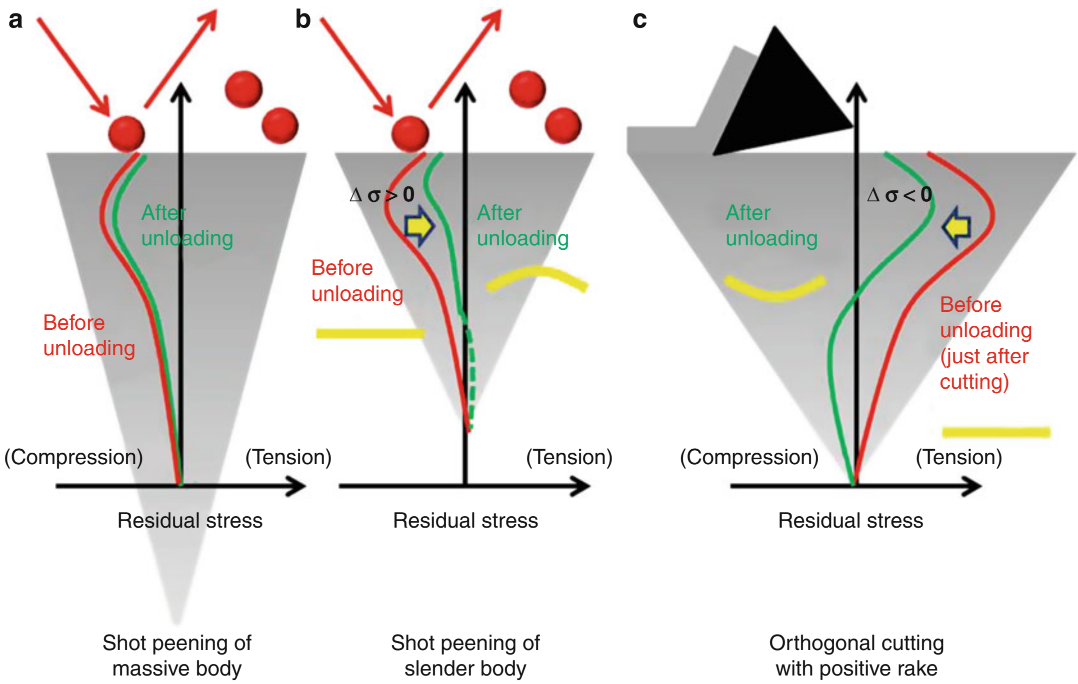
Residual Stress (Forming), Fig. 1 Perfect elastic recovery after unloading a tensile force





Residual Stress (Forming), Fig. 2 Stress field after unloading

are removed. In contrast, if the material has been strained permanently beyond the limit of plasticity, the stress field of the material cannot recover to the initial state but transits to a third state, as illustrated in Fig. 2c, owing to the constraints on deformation during unloading. In this state, the stress field differs from that during loading, but the static equilibrium



Residual Stress (Forming), Fig. 3 Examples of residual stress

condition expressed by Eq. 2 is also satisfied at every point inside the material. The macroscopic deformation that occurs during unloading is the springback. The deformation during unloading is mainly the elastic deformation, but plastic deformation may take place in some cases.

If a part or several parts in a body have been *strained permanently* beyond the limit of plasticity and the external forces and moments are removed, the material in the overstrained region and around it will, in general, be subjected to inherent stresses which are then called residual stresses (Nadai 1963). This description is exact from the macroscopic viewpoint; however, from the microscopic viewpoint, the residual stress in each grain may be different, even in a tensile test that induces perfectly uniform deformation from a macroscopic viewpoint as shown in Fig. 1. In such a case, residual stress can be understood as a stress mainly due to the different state of stress existing in the variously oriented crystals before unloading (Johnson and Mellor 1962).

Examples of Residual Stress

The thickness distribution of residual stress after shot peening is schematically illustrated in Fig. 3a. Although the mechanism of the development of residual stress during shot peening has not been consistently clarified, it is regarded that, although residual stress at the bottom of the crater or at its edge area after an indentation of a sphere is tensile, numerous impacts by hard spheres cause compressive residual stress in the surface region, which delays the initiation of cracks at the surface of a product upon cyclic loading during use (Yoshizaki 2009). The plastic deformation zone in shot peening is limited to a thin layer at the surface, and this layer is strongly constrained by the much larger nondeforming region adjacent to the surface layer. Thus, the compressive residual stress has a limited effect on changing the geometry during unloading. In the case of a thinner material, it will be plastically deformed out of plane by numerous shots which result in the geometrical change of sheet. Also, the effect of compressive stress induced by the impact of numerous shots has a greater influence on changing the geometry during unloading. The decrease in compressive stress during unloading, which is equivalent to a positive stress increment $\Delta\boldsymbol{\sigma}$, results in a positive strain increment. Thus, the expansion of the surface induced by the increase in strain in unloading results in the curling of a thin body, as shown in Fig. 3b. Above deformation during loading and unloading is the fundamental principle of the change in geometry during the hammering of a sheet, incremental forming, and shot peen forming (Kopp and Schulz 2002).

For comparison, the thickness distribution of residual stress in the cutting direction after orthogonal cutting is schematically illustrated in Fig. 3c. The stress immediately after orthogonal cutting is positive when the rake is positive and is reallocated in a complex distribution in the thickness direction during unloading (Shirakashi et al. 1993). The stress increment during unloading is negative, meaning that compressive strain increases in the cutting direction. Thus, if the material is thin and the bending stiffness is small, the curling of the material takes place, as shown in Fig. 3c, which is the opposite direction to that in the case of hammering a sheet.

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Residual Stresses in Machining Operations

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Definition

By definition, the residual stresses are multiaxial static stresses that exist in an isolated component without any applied external force or moment, and they are in mechanical equilibrium. Residual stresses are the response to the mechanical and structural history of the component during its manufacturing (metal casting, metal forming, machining, heat treatment, etc.) and in service when submitted to external loadings (thermal, mechanical, and chemical). They are caused by the elastic response of the material to the heterogeneous plastic deformation at any scale of the component or structure.

Theory and Applications

Introduction

The quality of mechanical components depends on large extend on the surface integrity, which is characterized by the mechanical, metallurgical, and chemical states of the machined affected layers (Jawahir et al. 2011). The residual stresses, together with the hardness, yield stress, tensile strength, etc., characterize the mechanical state of the machined affected layers. The study of machining operations inducing residual stresses is particularly important when critical structural components are machined, especially, if the objective is to reach high reliability levels and long service life.

Both magnitude and distribution of the residual stresses in the machined components can be critical for the functional performance and life of components. Residual stresses can cause a decrease in the static and dynamic strength, a decrease in the corrosion resistance, a dimensional instability (part distortion), changes

Residual Stresses in Machining Operations, Fig. 1 Effects of the residual stresses (Outeiro 2002)

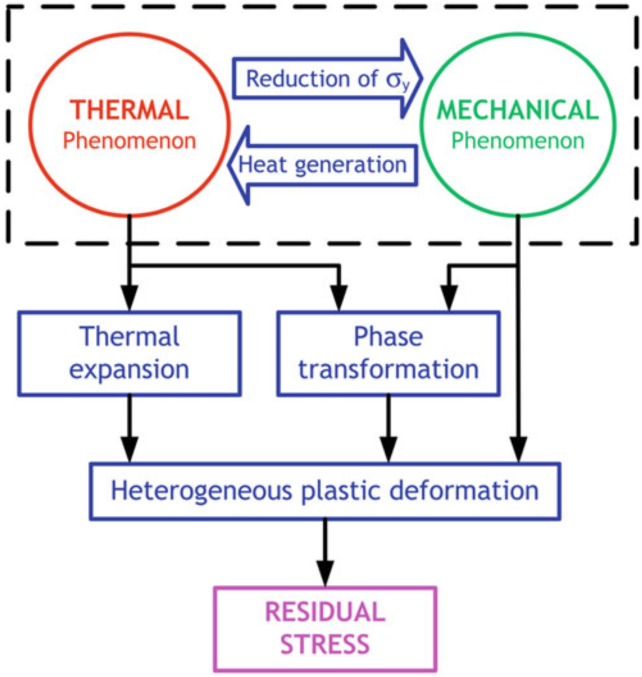
in the magnetically properties, etc. (Brinksmeier et al. 1982) (see Fig. 1). Therefore, they must be taken into consideration during the design and manufacturing of components. In general, tensile residual stresses at the components superficial layers are unwanted, since they can induce premature fatigue and corrosion failures. On the contrary, the compressive residual stresses at the components superficial layers are beneficial, since they increase the fatigue and corrosion resistances.

Residual stress distribution in the machined components results from the machining history but also from the previous materials processing. The machining history consists of a sequence of machining operations (turning, milling, drilling, etc.) and corresponding machining parameters. In this sequence, the effect of successive machining passes should be also considered (Guo and Liu 2002). Defining a logical machining sequence for a given component, the resulting residual stress distribution in the machined surface layers will depend on the machining parameters used in each operation, being the strongest contribution given by the last one. The final goal is the selection of the optimal machining parameters in order to obtain an acceptable/desirable residual stress distribution in the component.

Mechanisms of Residual Stress Formation in Metal Cutting Operations

Residual stresses in metal cutting are essentially generated by heterogeneous plastic deformation existing in a component. This plastic deformation results from the combined action of the thermal and mechanical phenomena generated by metal cutting operations. These two phenomena are usually designed as the origins of the residual stresses. Usually, phase transformation is also considered as other origin of the residual stresses. However, phase transformation is a consequence of the thermal and mechanical phenomena (see Fig. 2). Depending on the volume variation, it can generate both tensile and compressive residual stresses (Scholtes 1987).

The heat generated in machining, which is produced by plastic deformation and friction, represents the thermal phenomena. However, only the portion of the heat conducted to the workpiece can generate residual stresses. Usually, this heat will contribute to the formation of tensile residual stresses due to the thermal expansion and



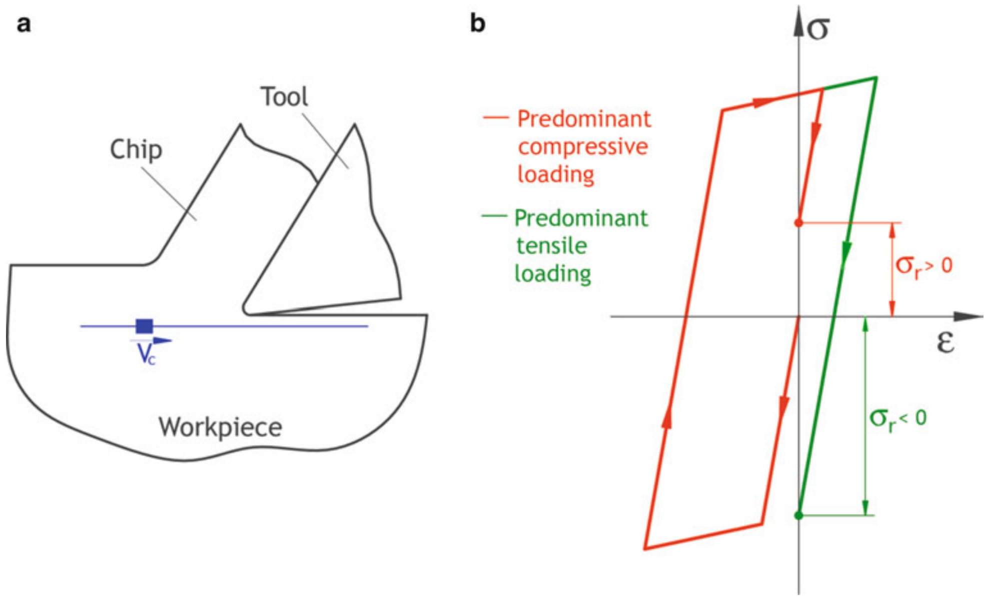
Residual Stresses in Machining Operations, Fig. 2 Schematic representation of the machining residual stress formation (Outeiro 2002)

contraction of the surface machined affected layers. Since the core of the workpiece is not deformed plastically, heterogeneous plastic deformation in the cross section of the component is created and consequently the residual stresses.

The mechanical phenomenon also induces heterogeneous plastic deformation due to the mechanical action of the tool over the workpiece surface layer. Liu and Barash (1982) proposed an approach to explain this action, which is based in the loading cycle that a material element is submitted through his movement along the cutting direction (see Fig. 3). According to this approach, the material element experiences deformation in compression when it is located ahead of the tool, followed by yielding. Then, it experiences deformation in tension when it passed through the tool tip, followed by an eventual second yielding. The residual stress in the machined layer will depend on the relative magnitude of the tensile and compressive loads. As shown (see Fig. 3), a predominantly compressive load will induce tensile residual stress, while a predominantly tensile load results in compressive residual stress. This cyclic loading is influenced by the work material properties and chip formation process.

Experimental Techniques for Determining the Residual Stresses

Several techniques can be applied to evaluate the residual stresses in engineering components/applications. These techniques can be classified into mechanical (hole-drilling, contour, curvature, and layer removal), diffraction (X-ray diffraction, neutron diffraction, synchrotron radiation), and others (magnetic, ultrasonic, Raman spectroscopy). The selection of the proper technique is a critical issue, and the decision will depend on practical (size of the component, availability of the equipment, level of expertise required, cost, etc.), material (type of material to analyze, surface condition, etc.), and measurement issues (spatial resolution, penetration, type of stress and gradient that can be analyzed/evaluated, accuracy of the measure) (Kandil et al. 2001). Most of the residual stress measurements have been carried out in metals, including cast iron, steels, light alloys (such as aluminum, titanium, and magnesium alloys), and nickel-based superalloys. However, there is also an increasing interest to measure the residual stresses in composite, polymer, ceramic materials and other nonmetallic materials.



Residual Stresses in Machining Operations, Fig. 3 Schematic representation of the residual stress formation in machining proposed by Liu and Barash (1982) which considers the mechanical action of the tool over the surface of the workpiece

The mechanical techniques rely on the monitoring of changes in component distortion, either during the generation of the residual stresses or afterward, by deliberately removing material to allow the stresses to relax (Withers and Bhadeshia 2001). Measuring these distortions using contact or noncontact techniques, the residual stresses can be calculated using the elasticity theory. The major advantages of these techniques are their relatively simplicity, quickness, and low cost, and they can be applied to wide range of materials. The major disadvantages are their low resolution, and they are destructive.

The diffraction techniques relay to the use of the radiation, such as X-rays and neutrons, to access to changes in the interplanar atomic spacing of a specific family of lattice planes and, therefore, to calculate the elastic (residual) strains and stresses (Noyan and Cohen 1987). Indeed, the presence of residual stress within a polycrystalline material causes elastic strain and thus changes in the spacing of the lattice planes from their stress-free value to a new value, which corresponds to the magnitude of the applied residual stress. Using X-ray or neutron diffraction, it is possible to measure the shift in the angular position of the diffraction peak in relation to its position when the material is without residual stresses. The interplanar atomic spacing can be calculated knowing the angular position of the diffraction peak and applying the Bragg law. Knowing the interplanar spacing, the elastic strain can be calculated, and applying elasticity theory, the residual stress can be determined. The major advantages of these techniques are their good resolution (in particular the case of X-ray and synchrotron), they operate without contact and, consequently, they are nondestructive (except when applying X-ray diffraction and electrochemical removal process to evaluate the residual stresses below surface). The major disadvantages are the high cost of the equipment and measurement and high level of expertise required, and they are limited to crystalline materials.

The other methods are not used so frequently for residual stress evaluation. In general such techniques like magnetic and ultrasonic are nondestructive, cheap, simple to use, very fast, and portable, which are well suited to routine inspections. However, the low resolution is their major limitation, in particular when compared with the diffraction techniques. The Raman spectroscopy is an exception. Its high resolution (less than 1 μm, thus higher than the diffraction techniques) makes it suitable to evaluate the residual stresses in extremely narrow regions of a few micrometers as is the case of fiber composites, providing basic information about the residual stress distribution from fiber ends to centers (Withers and Bhadeshia 2001). Unfortunately, the major disadvantages of this technique relay to its calibration and limited range of material that can be analyzed. Many other techniques are being developed for measuring residual stresses, most of which are still in the research and development stage.

From the range of techniques above described, the hole-drilling and the X-ray diffraction techniques are the most used in practice. A survey carried out in the United Kingdom (Kandil et al. 2001) covering a representative cross section of UK industry and academia shows that more than 55% use the hole-drilling and the X-ray diffraction techniques for residual stress analysis, because they fit most of the practical, material, and measurement issues. This survey also shows that almost 50% consider the residual stresses of high importance to their business, while 30% ranked them as of medium importance.

A relatively good agreement between the results of both hole-drilling and X-ray diffraction techniques is obtained, in particular in the interior of the samples (Nobre et al. 2000). However, the hole-drilling was found to be unsuitable to evaluate the residual stresses in very near-surface and also strong residual stress gradients, such as those generated by machining and some metal forming processes. The observed discrepancies between the residual stresses measured by both techniques are often attributed to the basic shortcoming of the hole-drilling technique, which is its limitation to residual stresses up to 60% of the material's yield strength (Beaney 1976). Because the drilling operation induces plastic deformations, the so-called plasticity effect can strongly affect the residual stress evaluation, which assumes linear elastic material behavior.

In conclusion, among all available techniques for determining the residual stresses in the machined affected layers, the X-ray diffraction, the synchrotron radiation, and the hole-drilling techniques are probably the most used. In the case of the two radiation-based techniques, they can provide very localized measurements due to their high spatial resolution and low penetration of the radiation in almost engineering materials. So, they are suitable to detect strong in-depth residual stress profiles, characteristic of the metal cutting processes. In the case of amorphous materials (like composites), the hole-drilling technique is a good alternative to the radiation-based techniques, although the abovementioned limitation of this technique.

Residual Stresses in Metal Cutting Operations

Residual stresses induced from metal cutting operations have been studied for several decades, resulting in a significant number of scientific publications covering a wide range of metal cutting operations (turning, milling, drilling, boring, etc.), work materials (plain carbon steels (Brinksmeier et al. 1982; Capello 2005; Henriksen and Ithaca 1951; Outeiro et al. 2006; Scholtes 1987; Torbaty et al. 1982), hardened steels (Matsumoto et al. 1986; Thiele et al. 2000; Umbrello et al. 2010), stainless steels (Jang et al. 1996; Outeiro et al. 2002, 2006), and superalloys (Mantle and Aspinwall 2001; Outeiro et al. 2008; Sharman et al. 2001, 2015; Sridhar et al. 2003)), tool geometries, tool materials, and cutting parameters. This section presents the residual stress distribution induced by several machining operations of different work materials, using several tool materials/geometry and cutting parameters.

Residual Stresses in Difficult-to-Cut Materials

The difficult-to-cut materials are a group of alloys that requires higher cutting energy when compared with low strength alloys (e.g., plain carbon steel). This group includes several alloys used for aerospace and nuclear applications, which can be classified into three major categories: nickel-based alloys (e.g., Inconel), iron-based alloys (e.g., austenitic stainless steels), and titanium-based alloys. As metal cutting is the purposeful fracture of the layer to be removed, not only the strength of the work material but also the strain at fracture should be considered. The product of these two mechanical characteristics indicates the energy that has to be spent in fracturing a unit volume of the work material, allowing chip formation. Due to high strength and fracture strain of such alloys, high cutting forces and heat are generated during their machining. Moreover, their low thermal conductivity and high mechanical and microstructural sensitivity to strain and stress-rate induce mechanical modifications and behavior heterogeneity on the machined surface, and this leads to unstable chip formation and vibrations. Their low thermal conductivity also leads to heat concentration in the cutting zone resulting in high localized temperatures. As a result, machining of such difficult-to-cut alloys when compared with machining of plain carbon steels (see Fig. 4) may induce (i) higher residual stress levels (sometimes reaching more than 1000 MPa at the component's surface), (ii) larger thickness of the layer affected by tensile residual stress, (iii) high work-hardening rate, and (iv) larger thickness of the work-hardened layer.

Such high tensile residual stress levels allow cracks to nucleate and grow, and thus decreasing the component's fatigue life. Moreover, the residual stresses are also responsible for the dimensional instability phenomenon leading to part distortion, which can pose major difficulties during assembly.

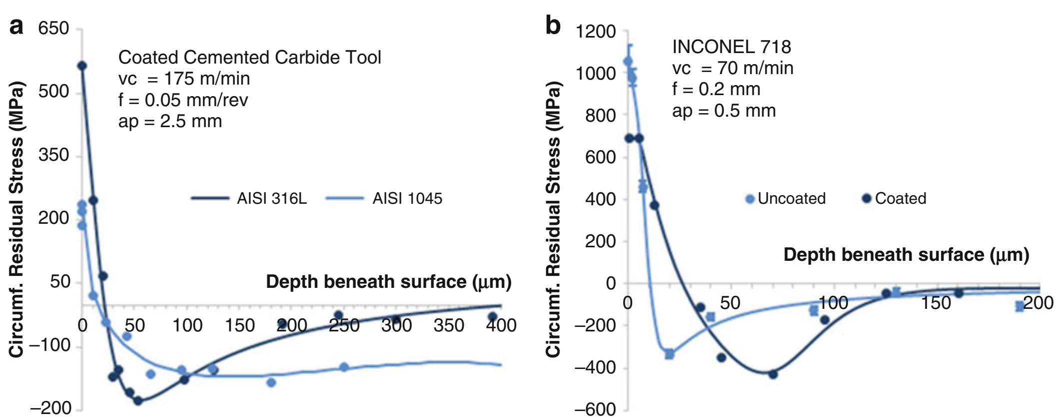
Residual Stresses in the Process Chain

Figure 5 shows the residual stress distribution induced by different machining operations used to produce a mold in H13 tool steel. As shown in this figure, the residual stress components of the tensor (parallel to the direction of the feed motion, σ_{11}, and perpendicular to feed motion, σ_{22}) generated during face milling of AISI H13 tool steel are predominantly compressive (see Fig. 5a), where their magnitude at the surface depends on the machining parameters employed. However, they can become tensile after EDM (see Fig. 5b). These residual stresses decrease and may become compressive after manual polishing or grinding (see Fig. 5c and d, respectively).

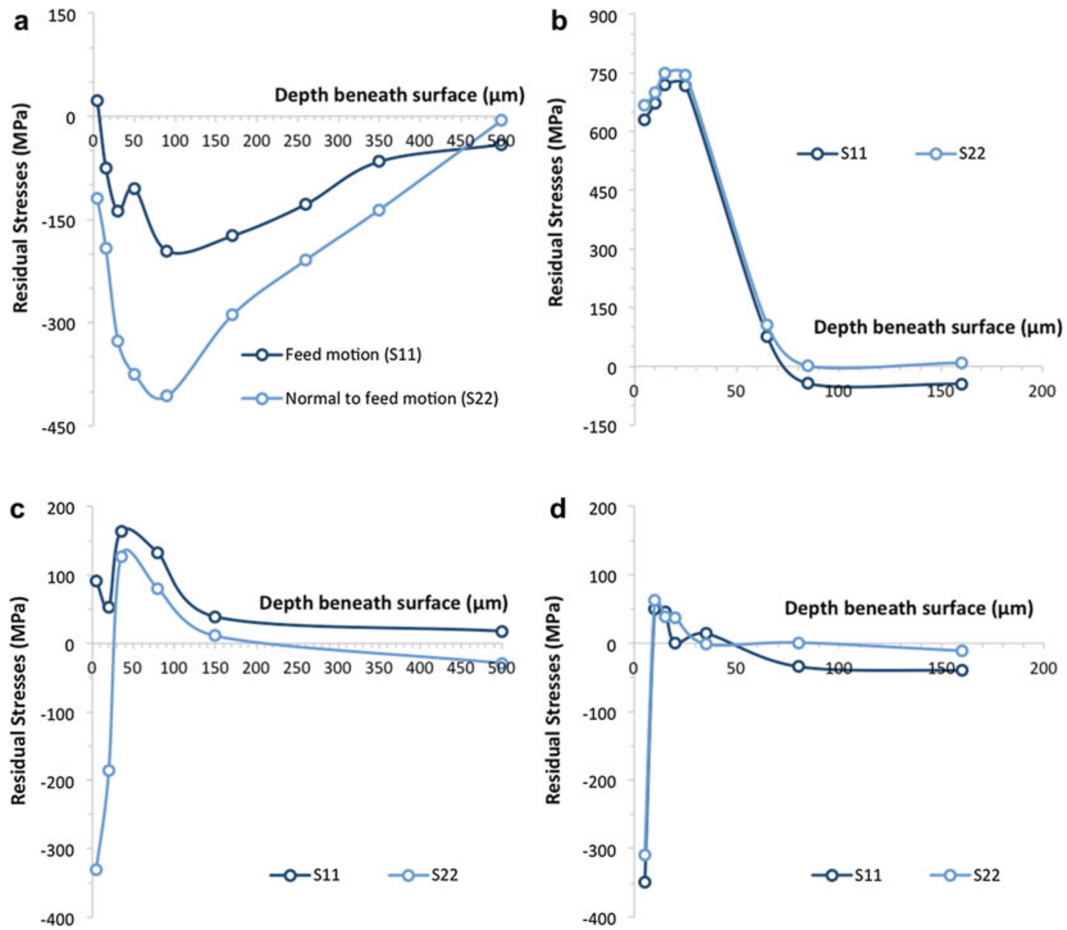
Besides, today a progressive replacement of the expensive and time-consuming EDM and manual polish/finish operations by high-speed machining technology is observed. Due to the low efficiency of cutting fluids at high cutting speeds, this technology can be associated with dry or near-dry machining conditions. This imposes new challenges for the proper characterization of the residual in the components' machined surface layer.

Influence of Cutting Parameters

The influence of the cutting speed (V_c), feed (f), and depth of cut (a_p) on the residual stresses has been investigated by several researchers. The



Residual Stresses in Machining Operations, Fig. 4 In-depth profiles of the residual stresses generated in turning of AISI 316L steel, AISI 1045 steel, and IN718, using coated and uncoated cemented carbide cutting tools (Outeiro et al. 2006, 2008)

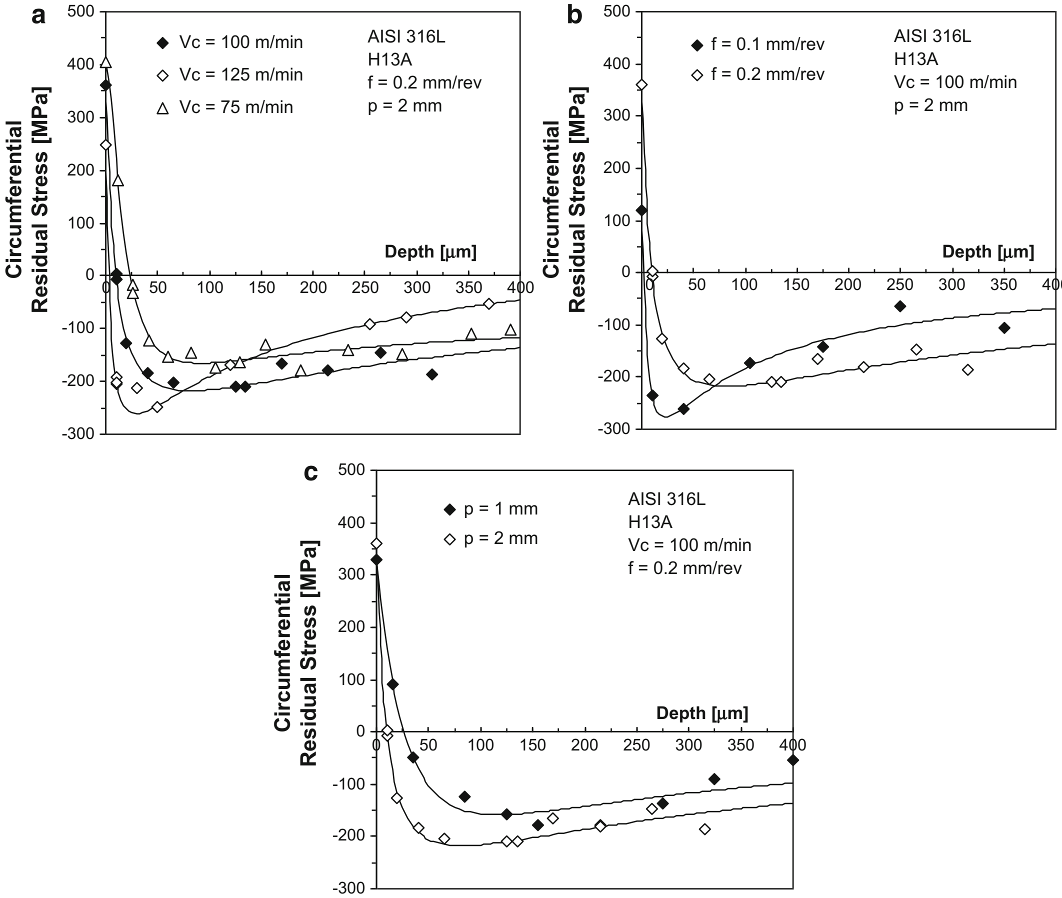


Residual Stresses in Machining Operations, Fig. 5 In-depth profiles of normal stress components (σ11 and σ22) in AISI H13 tool steel (Outeiro et al. 2007). (**a**) After annealing and milling. (**b**) After annealing, milling, quenching, tempering (50 HRC), roughing EDM, and finishing EDM. (**c**) After annealing, milling, quenching, tempering (50 HRC), and grinding. (**d**) After annealing, milling, quenching, tempering (50 HRC), roughing EDM, finishing EDM, and manual polishing

influence of V_c on the residual stresses is not evident. The results show that residual stresses can increase or decrease with V_c depending on the other cutting parameters, tool geometry/material, and work material (Outeiro 2002). Identical behavior is observed with a_p. In this case, surface residual stress remains constant or decreases with a_p (Outeiro 2002). In both cases (V_c and a_p), the thickness of the layer affected by tensile residual stresses slightly decreases with the increases of V_c and a_p (Outeiro et al. 2002). As far as the feed is concerned, its influence on the surface residual stresses seems to be more evident. In general, both the surface residual stresses and the thickness of the layer affected by tensile residual stresses increase with the feed (f) (Capello 2005; Outeiro 2002; Outeiro et al. 2002). Figure 6 shows an example of the in-depth residual stress profiles obtained by turning AISI 316L stainless steel, varying V_c (Fig. 6a), f (Fig. 6b), and a_p (Fig. 6c).

Influence of Tool Geometry and Tool Material (Coating)

Tool geometry as well tool material has an important role in the residual stresses generated in the machined surface. Several studies have been conducted to show the influence several



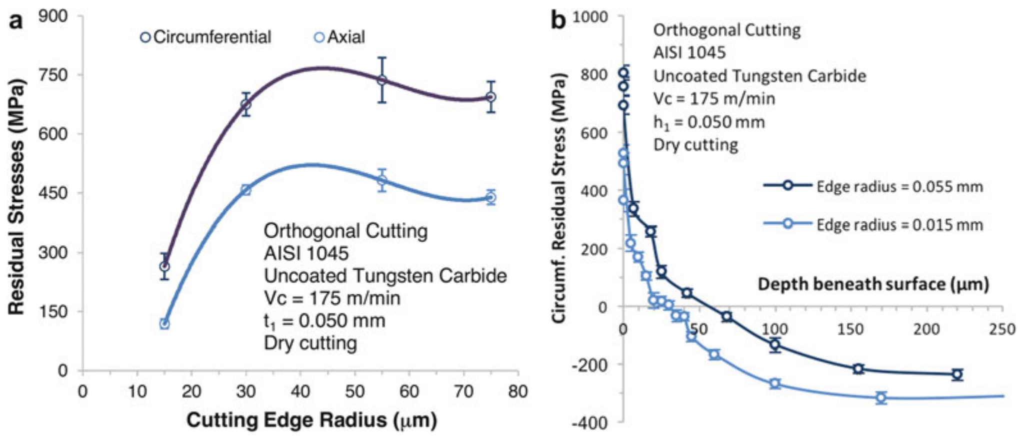
Residual Stresses in Machining Operations, Fig. 6 In-depth circumferential (cutting direction) residual stress profiles for different Vc (**a**), f (**b**), and a_p (**c**) (Outeiro et al. 2002)

tool geometry parameters on the residual stress distribution. For example, an experimental study on turning of three work materials performed by Capello (2005) shows that axial residual stress increases with the tool nose radius (r_ε) and decreases with the tool cutting edge angle (K_r). Another experimental study on turning AISI 316L stainless steel performed by Outeiro et al. (2010) shows that both axial and circumferential residual stresses increase when the cutting edge radius increases up to the value of the uncut chip thickness (40–50 µm), which corresponds to a ratio between the uncut chip thickness and the cutting edge radius equal to 1 (Fig. 7a). For larger cutting edge radius (when this ratio is less than 1), the residual stresses do not change significantly, being almost constant. These residual stresses are largely due to the plowing process. Moreover, Fig. 7b shows the variation of the circumferential residual stresses as a function of the distance from the machined surface. As seen in this figure, the residual stresses are maximal at the machined surface, and then they decrease as the distance from the machined surface increases, stabilizing around the residual stress value found in the work material before machining (in the range of 150–300 MPa in compression). This figure also shows that an increase in the edge radius from 15 to 55 µm causes an increase in the thickness of the tensile layer from 26 to 55 µm.

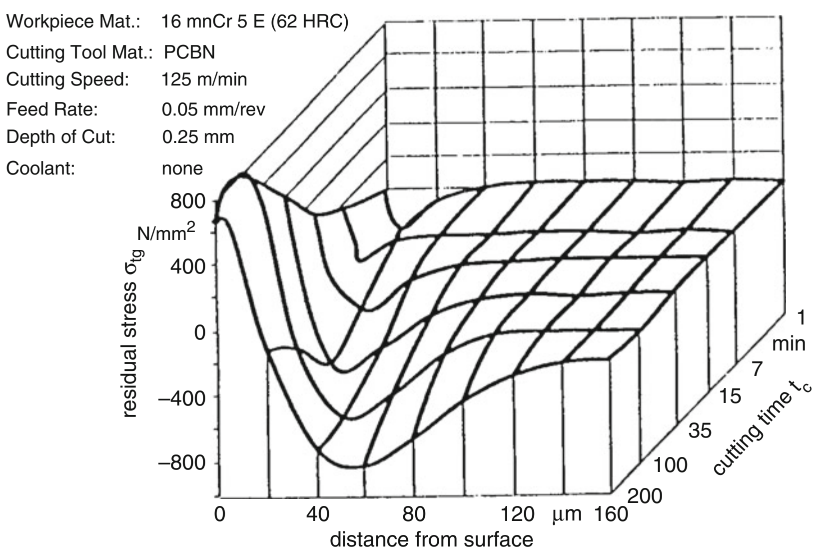
Concerning to the tool material, Fig. 4b shows that turning IN718 superalloy using coated (TiAlN coating) cutting tool when compared with uncoated tool generates higher thickness of the layer affected by tensile residual stresses, but lower surface residual stress value. As demonstrated by Outeiro et al. (2006), although the coated tool generated slightly less total thermal energy when compared to the uncoated tool, more heat is conducted into the workpiece when the coated tool is used. As a result, high temperatures and thermally affected layers are produced on the machined surface.

Influence of Tool Wear

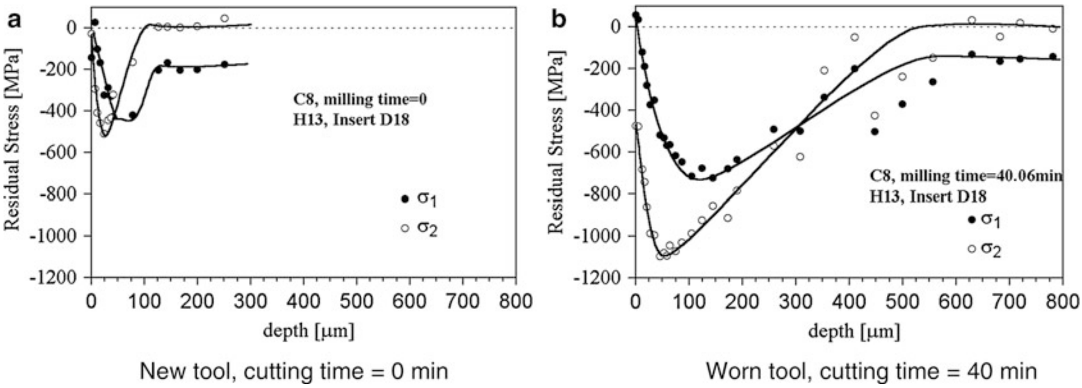
Figures 8 and 9 show the influence of tool wear on the in-depth residual stress profiles. With the increase of tool wear, the thermal and mechanical phenomena acting in the workpiece become more intense. The result of the mechanical action of tool on the machined surface is similar to the Hertz stress (Brinksmeier et al. 1994). So, as the tool becomes worn, the residual stress maximum below surface increases, and its location shifts



Residual Stresses in Machining Operations, Fig. 7 Influence of cutting edge radius on residual stresses at the machined surface (orthogonal cutting; AISI 1045; uncoated tungsten carbide; V_c, 175 m/min; h_1, 0.050 mm; dry cutting) (Outeiro et al. 2010)



Residual Stresses in Machining Operations, Fig. 8 Evolution of the residual stresses in function of the cutting time (Goldstein 1991). (**a**) New tool, cutting time = 0 min. (**b**) Worn tool, cutting time = 40 min



Residual Stresses in Machining Operations, Fig. 9 Effect of tool wear on residual stress profile in milling of H13 steel-coated carbide ($V_c = 80$ m/min, $f = 0.15$ mm/rev, and $a_p = 0.8$ mm) (M'Saoubi et al. 2008)

further below the surface. Depending on the amount of heat generated and of the thermo-physical properties of the tool and workpiece, thermal dilatations can be produced and may enough to plastically deform the superficial layer, which may result in an increase of tensile residual stress (Fig. 8).

Residual Stress Control in Practical Machining Operations

There is a need to develop a number of feasible means to control the residual stresses during practical machining operations. An example of such control resulted from an extensive study of the residual stresses obtained varying different machining parameters and tool geometry performed by Outeiro (2002) in turning operation of AISI 316L. In this study, the feed, tool nose radius, and tool cutting edge angle were the most influencing parameters on the residual stresses. The feed seems to be the parameter that has the strongest influence on residual stresses. In order to reduce the magnitude of the residual stress, the feed must be kept as low as possible. However, decreasing the feed decreases the material removal rate (keeping the other cutting regime parameters unchanged). Therefore, in order to increase the material removal rate without compromise, the residual stresses (sometimes even improving it) the depth of cut can be increased.

This finding allowed us to introduce the parameter f/p, defined as the ratio between the feed and the depth of cut. This new parameter can be used in the control process of the residual stress. As shown in Fig. 10a, the residual stress increases with the parameter f/p. Therefore, if the objective is to reduce the residual stresses, this parameter must be kept as low as possible.

Another interesting result is related with the equivalent tool cutting edge angle, K_r^{eq}, defined as the tool cutting edge angle of the equivalent cutting edge. This cutting edge replaces the major and minor cutting edges and the tool nose in the manner shown in Fig. 10b. As formulated by Colwell (1954), this equivalent cutting edge is defined as a straight line that connects the end of the major and minor cutting edges as shown in Fig. 10b. Once the equivalent cutting edge is constructed, the direction of chip flow is assumed to be perpendicular to this edge. Because the f/p parameter and K_r^{eq} have opposite evolutions, the residual stresses decrease with the K_r^{eq} angle. Similar results are also obtained by Capello (2005) who showed that residual stresses decrease with the major tool cutting edge angle, κ_r. This suggests that the effect produced by the same cutting tool and different values of feed and depth of cut, therefore, different K_r^{eq} angles, is equivalent to that produced by identical cutting tools having different κ_r angles.

It is interesting to note that there is a relationship between the residual stresses and the chip side-flow angle (η_s). This angle is defined between

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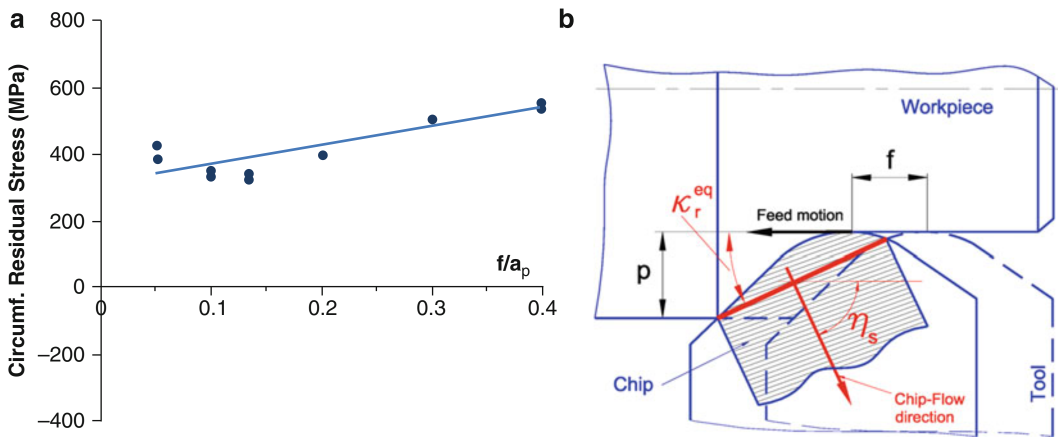
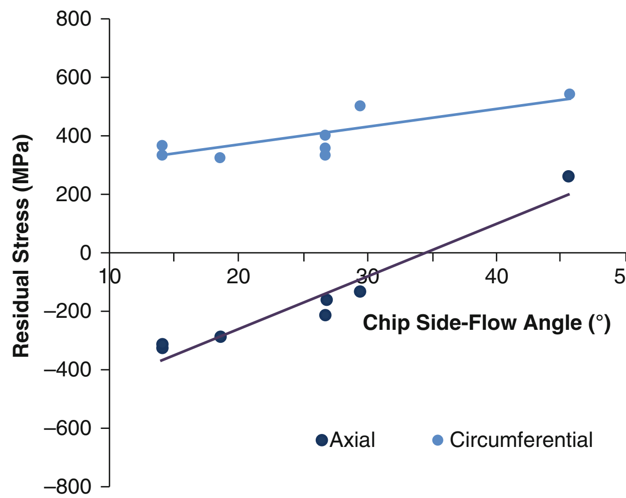


Residual Stresses in Machining Operations, Fig. 10 Influence of the f/p parameter in surface residual stresses when turning AISI 316L using uncoated tungsten carbide cutting tool (Outeiro 2002)



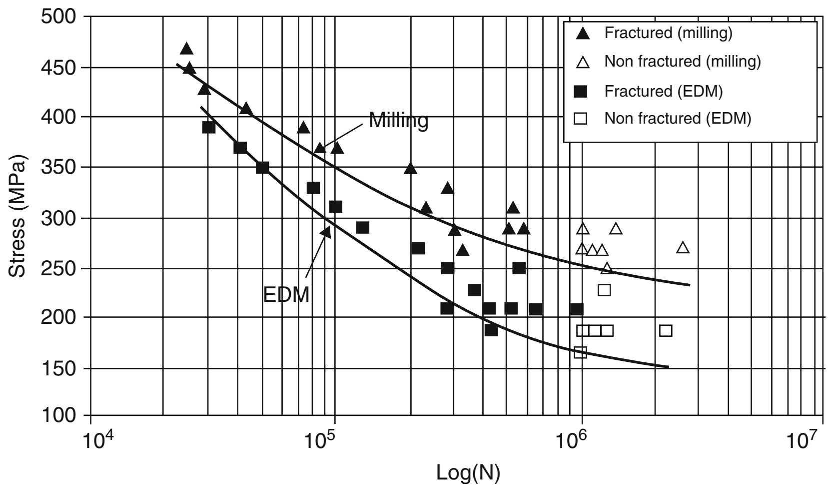
Residual Stresses in Machining Operations, Fig. 11 Relation between chip side-flow angle and residual stresses, when turning AISI 316L using uncoated tungsten carbide cutting tool (Outeiro 2002)

the chip flow direction and the direction of the feed motion, and it's measured on the tool rake face Fig. 11. As seen, the chip side-flow angle depends on the applied cutting conditions, in particular on the feed, depth of cut, tool cutting edge angle, and tool nose radius. These parameters are among those which have strong influence on residual stresses. Therefore, it can be deduced that there is a relationship between the chip side-flow angle and the residual stresses. Indeed, as shown in Fig. 11, the residual stresses increase as the chip side-flow angle increases. As a consequence, the chip side-flow direction can be used to control of residual stresses.

Influence of Residual Stresses in the Functional Performance and Life of Components

As known, compressive residual stresses are beneficial for fatigue endurance. For example, Ghanem et al. (2002) have investigated the role of residual stress state in two operations, namely, hard milling and EDM of a tool steel (SAEJ438b at 30 HRc). Three-point bending fatigue tests of the notched specimens revealed a loss of 35% in fatigue endurance in the case of EDM (Fig. 12).

In spite of the rather low cutting regime (4 mm diameter HSS cutter at $V_c = 30$ m/min and $f = 0.05$ mm/rev) in milling in this test, the effects of



Residual Stresses in Machining Operations, Fig. 12 Influence of machining on fatigue life (after Ghanem et al. 2002)

residual stress (−300 MPa in milling and +750 MPa in EDM) are obvious.

Cross-References

▶ Residual Stress (Abrasive Processes)
▶ Residual Stress (Forming)
▶ Surface Integrity

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Resolution

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Definition

According to the "International vocabulary of metrology" (JCGM 200:*2012* or "VIM"), **resolution** is the smallest change in a quantity being measured that causes a perceptible change in the corresponding indication. **Resolution** can depend on, for example, noise (internal or external) or friction. It may also depend on the value of a quantity being measured.

In a similar way, the **resolution of a displaying device** is defined as "the smallest difference between displayed indications that can be meaningfully distinguished."

Theory and Application

In metrology, the term **resolution** is usually directly associated with the resolution of a sensor or measuring equipment. If resolution is associated with another kind of equipment (e.g., the positioning resolution of a machine), it still has to be asserted/verified with a capable measuring equipment.

In this sense, resolution refers to the smallest feature of the measuring quantity that can be acquired/distinguished (i.e., resolved) with the sensor or measuring equipment. The resolution of a measuring equipment influences directly its measurement uncertainty, as it defines the uncertainty limits that are achievable with the equipment (Pfeifer and Schmitt 2010).

The term resolution should be distinguished from other well-defined metrological terms, such as accuracy, precision, uncertainty, and quality of a measuring equipment (Bucher 2004). Resolution, accuracy, and precision have influence on the measurement uncertainty of a measuring equipment and thus contribute to the quality and capability of the measurement, but they have different meanings.

The determination of the overall resolution of some measuring equipment may require more efforts, as it involves the combination of the resolution of different measuring system components. For example, the optical resolution of optical measuring systems may be calculated by the combination of the resolution of different components (e.g., their MTF – modulation transfer functions), such as lens resolution, sensor resolution, data transmission resolution, and display resolution.

It is very common to confuse the definition of optical sensor resolution with other optical system features. Different optical sensors are conceived to detect spatial differences in electromagnetic energy, as, for example, digital cameras (CCD and CMOS), tube detectors (vidicon and plumbicon), and pyroelectric and microbolometer detectors. Such optical sensors are able to resolve differences in the variations of the electromagnetic field. This ability depends mostly on the size of the detecting elements and not on their total number.

Spatial resolution for optical sensors is thus (or at least should be) typically expressed in line pairs per millimeter (lp/mm) or lines of resolution, or even as a MTF curve. Confusion arrives among non-technicians by using the number of pixels of the optical sensor to describe the camera resolution. This would only be acceptable if all camera sensors were the same size, and still the other camera components would remain the same or equivalent (e.g., lens resolution). Since they are not, using the camera number of pixels for defining the camera resolution can lead to misunderstandings and wrong conclusions. For example, a 2 megapixel camera with pixel size of 20 μm will have a worse resolution than a 1 megapixel camera with pixel size of 8 μm (supposing the rest of the camera hardware is equal) (Stemmer Imaging 2011).

Spatial Resolution in Imaging

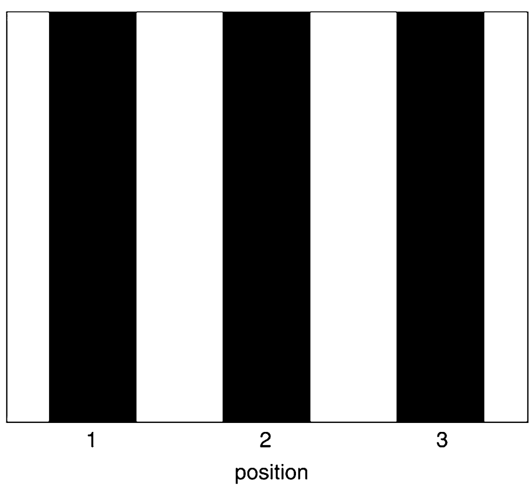
Spatial resolution in imaging is a measure of how close two identical bright objects can be approximated before they can no longer be resolved due to vanishing image contrast (modulation) (Gonzalez and Woods 2002). The concept of modulation transfer function (MTF) can be used to describe spatial resolution mathematically.

To explain the concept of the MTF, we assume a test pattern, a grating structure, with a certain spatial frequency as shown in Fig. 1.

If we measure the brightness distribution of the test pattern illuminated with white light from behind, we get a sinusoidal line profile due to diffraction effects (Fig. 2 top). If we image the test pattern with a real lens and measure the brightness distribution again, we get a line profile as shown in Fig. 2 (bottom). Due to imperfections of the lens, the amplitude is reduced to 50% at this certain spatial frequency. The difference between the maximum and minimum in amplitude of the line profiles is called contrast or modulation.

The MTF is defined by:

$$\mathrm{MTF}(q) = \mathrm{image\ \ contrast}/\mathrm{object\ \ contrast} \quad (1)$$



Resolution, Fig. 1 Test pattern

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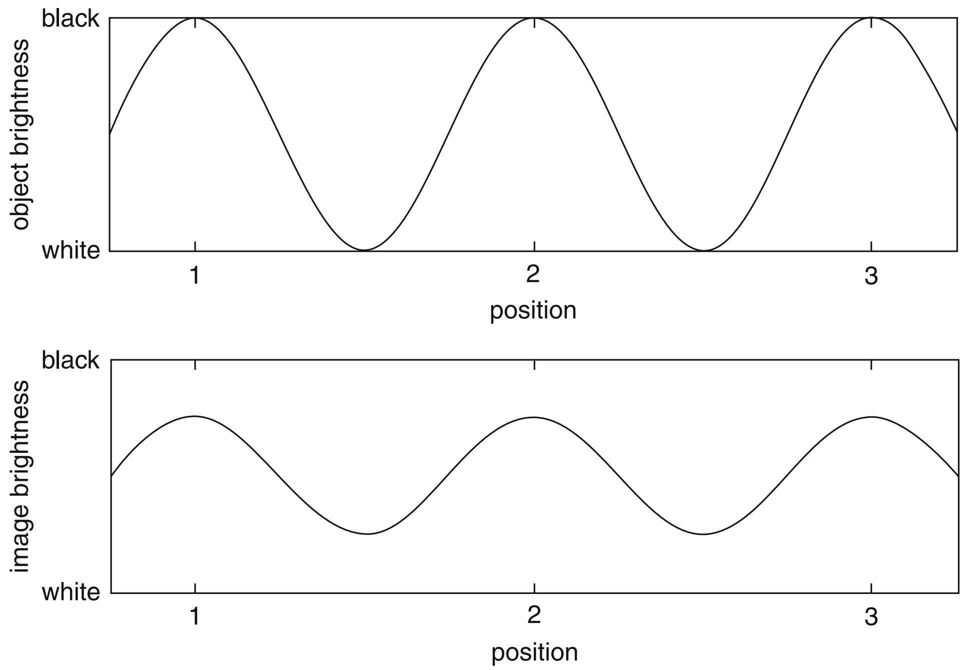


Resolution, Fig. 2 Line profiles of test pattern. Object line profile (*top*) and image line profile (*bottom*)

with spatial frequency q. The MTF of a system consisting of various components is calculated by multiplying the MTF of each component, e.g.,

$$\begin{aligned} \mathrm{MTF}_{\mathrm{system}}(\mathrm{q}) \quad & amp; = \mathrm{MTF}_{\mathrm{sensor}}(\mathrm{q}) \\ & amp; \quad {}^{*}\mathrm{MTF}_{\mathrm{aperture}}(\mathrm{q}) \\ & amp; \quad {}^{*}\mathrm{MTF}_{\mathrm{algorithm}}(\mathrm{q}) * \ldots \end{aligned} \tag{2}$$

The weakest component dominates the systems MTF.

As an example, Fig. 3 shows MTF graphs for the imaging hardware of a computed tomography system (Buzug 2008). The x-axis represents the spatial frequency in 1/mm; the y-axis represents the MTF(q). The MTF is normalized to 1. The $\mathrm{MTF}_{\mathrm{imaging\ hardware}}$ is calculated according to formula (2). The first zero of the MTF is called cutoff frequency. Spatial frequencies smaller than the cutoff frequency cannot be resolved.

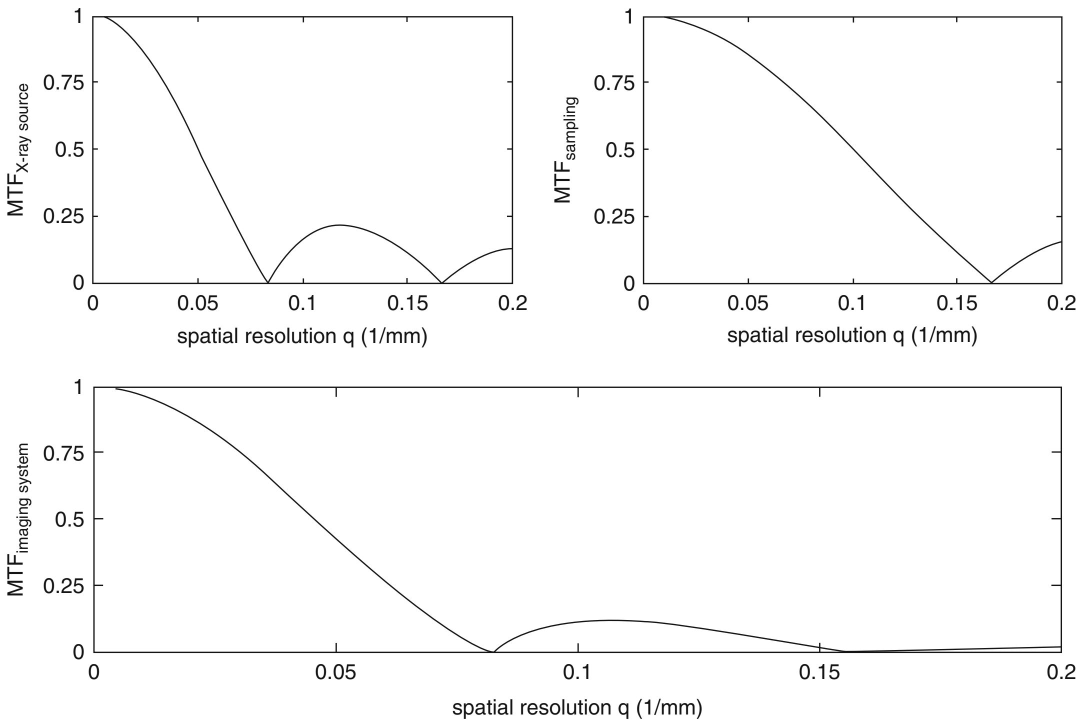
The optical properties of, e.g., lenses change from the center to the corner. To describe this behavior a different graph is used. Instead of spatial frequency the x-axis represents the distance from the image center. The graph contains at least two pairs of lines, each pair at a certain spatial frequency. A pair consists of a line for sagittal and tangential orientation. An example of an optical lens system is given in Fig. 4.

In principle one can say the following:

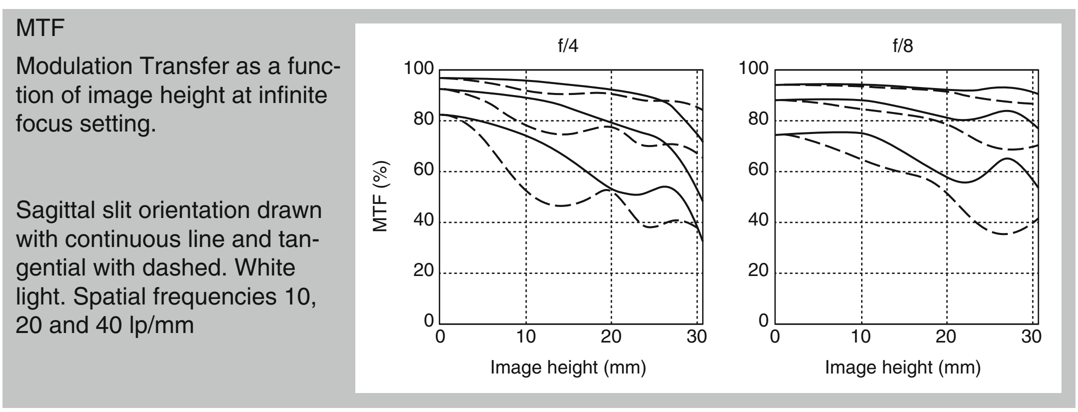
- The higher the MTF, the better the optical system.
- The nearer tangential and sagittal curves are, the better the imaging power.
- A modulation of 20% is a limit for inspection purposes.

Resolution Targets

A common way of testing the resolution of imaging systems is by using 1951 USAF resolution targets (see Fig. 5). They consist of horizontal and vertical bars organized in groups and elements. Each group is composed of six elements and each element is composed of three horizontal and three vertical bars equally spaced with one



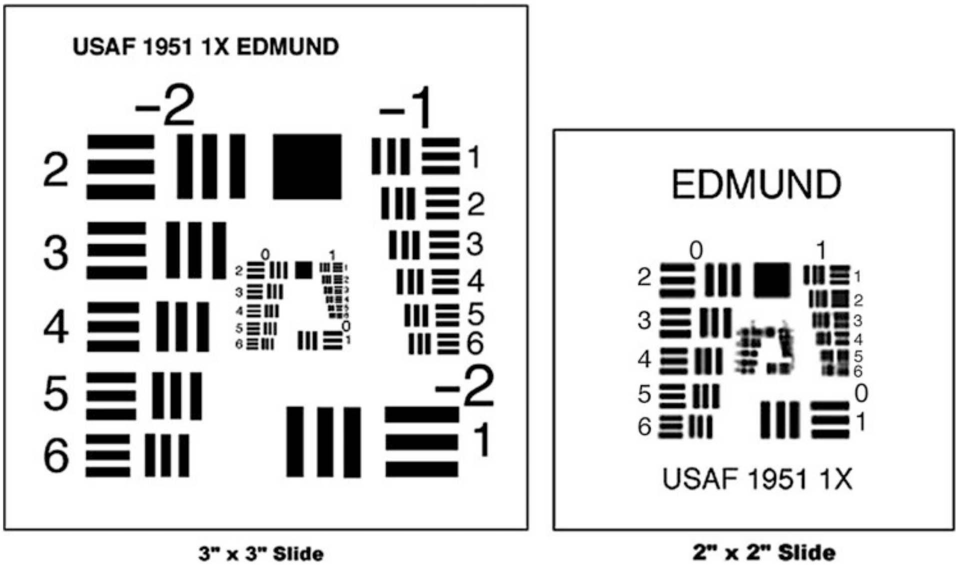
Resolution, Fig. 3 Calculated MTF curves of the imaging system of a computed tomography system



Resolution, Fig. 4 MTF of a lens system (Source: Hasselblad 2016)

another. The resolution is based on bar width and space. One line pair (lp) is equivalent to one black bar and one white bar. Vertical bars are used to calculate horizontal resolution and horizontal bars are used to calculate vertical resolution. The resolution limit of the imaging system is achieved directly before the black and white bar groups begin to blur together. Quantitatively, this resolution limit can be calculated by (in terms of line pairs per millimeter or lp/mm)

$$\text{Resolution} = 2(\text{GroupNumber} + (\text{ElementNumber} - 1)/6) \tag{3}$$



Resolution, Fig. 5 1951 USAF resolution target (Source: Edmund Optics 2010)

Cross-References

- ► Accuracy
- ► Measurement Uncertainty
- ► Metrology
- ► Precision

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Resource Efficiency

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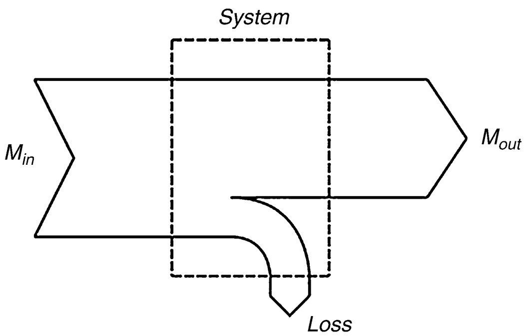
Definition

Resource efficiency is the ratio between the useful output (product) and the resource input of a system.

Theory and Application

Introduction

Resource efficiency serves as a performance criterion of the corresponding system. Figure 1 illustrates a generic material flow diagram of a system, with the system boundary shown by the dashed line.



Resource Efficiency, Fig. 1 General material flow in a system

Resource efficiency is a dimensionless metric with values between 0 and 1 (0–100%) and defined as shown in Eq. 1.

$$\eta = \frac{M_{\mathrm{out}}}{M_{\mathrm{in}}} \quad (1)$$

Applications in Production Engineering

In production engineering, the system of interest is usually the production process and/or the production system. In several cases, not all material input flows can be transformed into useful products or by-products that can be used as an input for other processes. Melting of metal is often linked with certain small losses (e.g., some metal losses within the slag) (Saeed-Akbari 2011). Also not all auxiliary material flows can be processed in a closed loop. An example for auxiliary material losses is the losses of metalworking fluids sticking on the workpiece surface when the workpiece enters the next process step without being recovered by other processes (e.g., cleaning) (Dettmer 2004; Petuelli 2002).

Cross-References

- ▶ Eco-efficiency
- ▶ Energy Efficiency

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Reuse

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Synonyms

Reprocess; Re-utilize; Second-hand use

Definition

Reuse is a product end-of use alternative. Reuse is defined as the transfer of a used product to a new user.

Product reuse implies that a product will preserve its original structure and likely will be used for its original purpose. Although used products can be used as is, processes such as cleaning and minor maintenance might be considered before beginning another usage cycle. Reuse differs from recycling in that it preserves both the material value and the functional value of a used product (Fig. 1).

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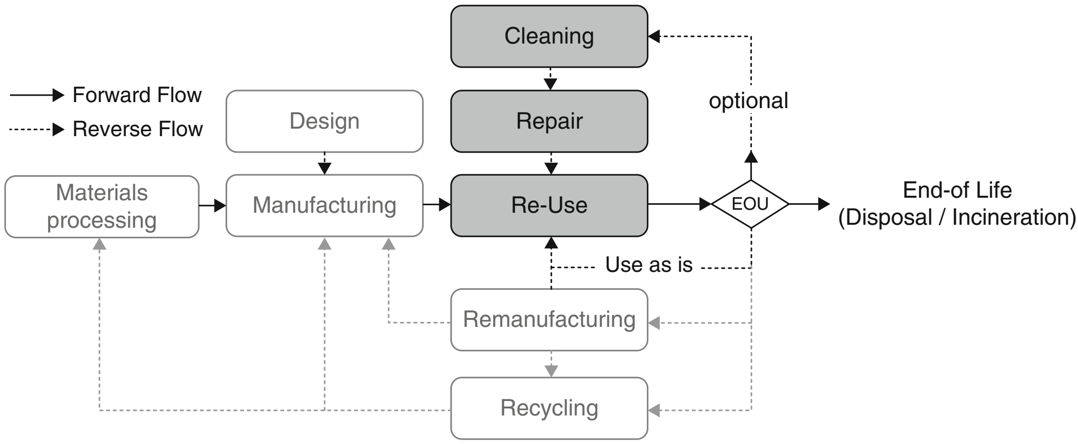

Reuse, Fig. 1 Reuse as an alternative in the product life cycle

Theory and Application

The concept of reuse is relatively simple; a used product is transferred from one user to another, with generally little intervention in between the two use cycles. The fact that the product is reused as-is and, therefore, no additional resources are consumed makes this end-of-use strategy one of the best from an environmental perspective. However, product design characteristics that promote reuse are less well understood. Certainly, product reuse is highly dependent on the time varying value of a product, and reuse will only be pursued if a second user believes that there is more value in the used product than its resale cost. The value of a product is affected by exogenous factors such as market forces, availability of competing products, customer perception, and opportunities for remanufacturing/refurbishing/recycling, as well as endogenous factors such as initial product quality, product wear/aging, and product reliability. In general, used products retain significant functional and material value that is invested during product design and manufacturing; this value is entirely lost when a product is discarded. An understanding of how value changes during the product life cycle will allow designers to create products that avoid excessive value erosion and will allow companies to anticipate business opportunities when recovering used products that still have significant value. Further information on reuse is provided in Kumar et al. (2007), Ilgin and Gupta (2010), and Sasikumar and Kannan (2008).

Secondary Market for Used Products

The diversity of used products that are commercialized for a second use is increasing. When understanding the secondary market of used products, it is important to characterize the type of product and the transaction channel utilized. There are two types of products that can be reused in secondary markets: products that constantly gain value overtime, such as antiques and collectibles, for instance, and durable products that lose value but are still tradable. Nowadays, durable goods such as cars, appliances, books, clothes, furniture, and college textbooks are widely traded in secondary market channels.

Used products are mainly commercialized through two transaction channels. In the first channel, a retailer buys used products from old users and sells them to new ones for a profit. In the second channel, the customer or new user can buy the used product directly from the old user without intermediaries (Yin et al. 2010). In both channels, the price of the new product version and value added by new features or capabilities as well as the services provided by the retailer are decisive to promote or discourage a secondary market of used products (Kogan 2011). When creating a secondary market for used products, three factors are of special attention for a successful implementation: (a) the commercialization channel, (b) the distribution channel, and (c) the costumer's demand for these used products.

The **commercialization channel** mostly used is the electronic commerce or e-commerce. Successful companies such as eBay and Amazon have broadened the opportunities to exchange a variety of new and used products online. The e-commerce has facilitated a close relationship between sellers and buyers. Amazon, as one of the largest online retailer, based its commercialization strategy on diversity in selection, low prices, and convenience for deliveries (Bezos 2011). In the same way, eBay supports its strategy in online auctions and other online interactions involving the community. With a higher availability of online resources to commercialize products, a growing stock of used products, and an increasing need for reducing the amount of waste sent to landfills, the opportunities to create businesses are enormous.

In reference to the **distribution channel**, three strategies are commonly used: original manufacturers' direct distribution, distribution through manufacturer's own retailers, and distribution through independent retailers. In all cases, the reverse and forward logistics to pick, store, and ship the used products are the core of the business. Retailers play a key role in the growth of secondary markets of used products. Because of their closeness to customers, retailers can serve as a direct channel for collecting not only the used products but also feedback from trends and patterns of use. For instance, libraries are the main source of distribution for used textbooks and repair shops are decisive in the commercialization of used vehicles and computers. The incentives provided and negotiation with retailers might affect directly the revenues obtained by the manufacturers and retailers as well as encourage or discourage customer acceptance (Shulman and Coughlan 2007).

The **customer's demand** for used products is highly tied to green consumers whose perception of product value is still high. The demand for used products might also be incentivized when a new set of customers intends to buy the product every certain period: for instance, students per each cohort and players of video games. The green consumers are willing to either continue using the used product for its original purpose or find a new function for it. This is the case of Goodwill Industries International, the second largest non-profit organization in trading used products such as clothing, furniture, dry goods, and sporting goods in the USA. Goodwill, with total revenues around $4 billion in 2011, has based its operation on products donated and bought by the community. Every year, around two billion pounds of clothes and household goods are diverted from landfills.

The reuse of products in secondary markets also entails some challenges for manufacturers, retailers, and even researchers. The availability of used products with lower prices in the market that compete directly with new products, the pricing of those new products, and frequency to upgrade versions of a product are some of the topics that are the subject of concern for manufacturers. When e-commerce is the only source of contact with the customers, the customer service is totally dependent on the supply chain logistics. Thus, the continued process improvement, development of innovative software applications, and cost reductions become critical to compete in the current aggressive internet markets. Issues such as the impact of secondary markets in the supply chain, the impact on the strategy of original manufacturers, and retailers are topics of research interest.

Cross-References

- ▶ Recycling
- ▶ Remanufacturing

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Re-utilize

► Reuse

Reversal

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Definition

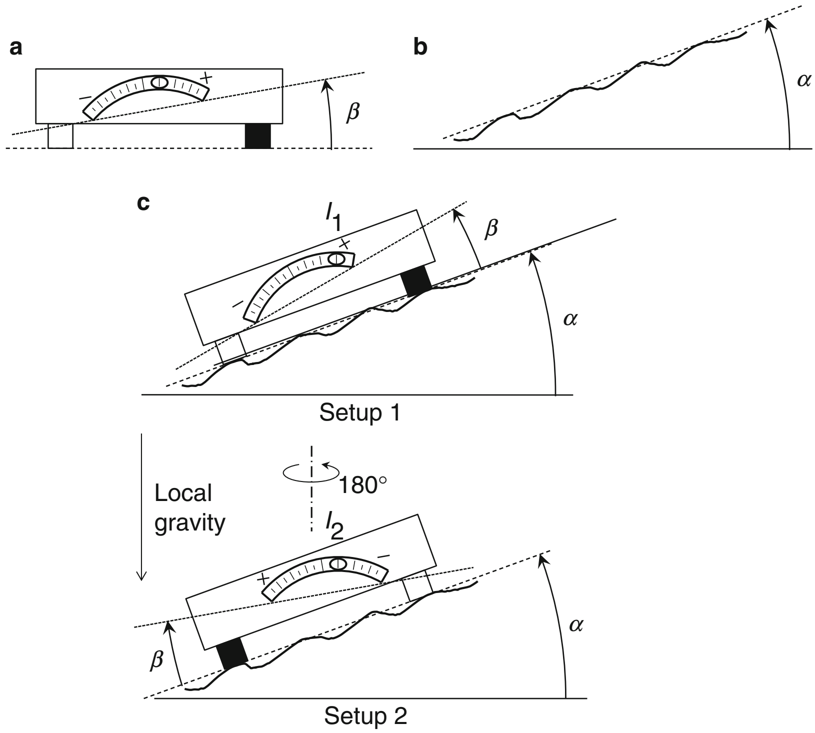
Error separation techniques refer to a wide body of techniques used, for example, in dimensional and machine metrology, to distinguish between otherwise superposed error sources, typically those from the measurand and those from the instrument. A common context is the measurement errors of an instrument and the errors of the measured object (or artifact). In this case the object errors are the primary measurand, and the instrument errors are the secondary measurand or by-product of the process. Another context is where the primary measurand is the error in the movement of a mechanism and the errors of an artifact, which will be measured by the mechanism fitted with some measurement sensors such as a dial indicator or touch-trigger probe, constitute the secondary measurand (the by-product). In both cases the measurement data is simultaneously affected by the errors of both the instrument/mechanism and the object/artifact. In the literature, examples of error separation techniques other than reversal methods are closure, difference techniques, multistep and multiprobe with possible overlap in the principles used (Evans et al. 1996; Marsh 2010). The use of an uncalibrated (only nominally known) artifact presents practical advantages. It is the making of two silk purses from two sow's ears.

In reversal methods a judicious change in the relative location of the sensor and object/artifact to the instrument/machine followed by the repetition of the measurement usually provides the means to distinguish between the errors. Such change is referred to as inversion, reflection, rotations, etc.

An attempt at a formal definition follows (see Evans et al. 1996) a technique where a mechanical manipulation with respect to a suitable degree of freedom other than the sensitive direction of the indicator results in a sign change in one component of the errors contributing to the indicator readings thus allowing the graphical or mathematical separation of the contributing errors. The necessary conditions for success are as follows: "(1) the indicator output must be a linear combination of signals representing the measurand and the systematic error; (2) a physical adjustment of the measurement system must be made which changes the sign of one component of the indicator output; (3) the measurement system must be stable through the physical adjustment; and (4) a metric must be independently realized, i.e., the indicator must be independently calibrated."

Theory and Application

Only some examples will be presented here together with a list of other related techniques for further reading. The techniques presented consist in remeasuring the artifact using specially selected relative changes in orientation (angular components) such that the unknown error sources of the artifact and of the measuring system can be separated mathematically. The examples will be studied in a little more detail primarily from a



Reversal, Fig. 1 Level reversal: (**a**) the level with its internal error $\beta = 10°$; (**b**) the measurand, a surface at an inclination $\alpha = 20°$ relative to the local horizontal; (**c**) the two measurement setups where a reversal of 180° is used relative to the local gravity

theoretical standpoint and via simulations in order to illustrate the method but without attempting to offer a generalization. In particular, uncertainty and setup aspects are considered. Readers can find many more examples of reversal techniques in the reference list.

Level Reversal

A simple example of reversal technique is level reversal illustrated in Fig. 1. Normally the indication of the level should correspond to the surface inclination relative to local gravity. However, because of a potential assembly orientation error between the level's banana-shaped glass vials and the line between the mechanical seats of the level outer body, those contacting the measured surface, a systematic error occurs. Reversal of the level consists in a rotation around an axis parallel to gravity which is the zero inclination reference for a surface perpendicular to gravity.

The indication for setup 1 is the sum of the surface inclination and the internal error of the level (Eq. 1), whereas for setup 2 the effect of the measurand, i.e., the surface inclination, on the indication is reversed, but the effect of the level's systematic error is preserved (Eq. 2):

$$I_1 = \alpha + \beta \tag{1}$$

$$I_2 = -\alpha + \beta \tag{2}$$

where

- I_1 and I_2 are the indications read on the level
- β is the instrument systematic error
- α is the true value of the surface inclination relative to local gravity (the measurand)

Equations 1 and 2 are solved, firstly, by their addition and, secondly, by their subtraction, to yield a solution for the measurand and the level's systematic error:

$$\alpha = \frac{I_1 - I_2}{2} \tag{3}$$

$$\beta = \frac{I_1 + I_2}{2}. \tag{4}$$

In matrix form Eqs. 1 and 2 become

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$$\begin{bmatrix} I_1 \\ I_2 \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ -1 & 1 \end{bmatrix} \begin{bmatrix} \alpha \\ \beta \end{bmatrix} \tag{5}$$

$$\boldsymbol{I} = \boldsymbol{M}\,\boldsymbol{A}. \tag{6}$$

Although somehow an overkill in this simple case, such a system can be analyzed numerically to verify solvability through the condition number, κ, of the system's identification matrix $\boldsymbol{M}$. In this case $\kappa = 1$ which is ideal for finding a solution which does not amplify the uncertainties present in the input data. The solution is simply obtained by matrix inversion

$$\begin{bmatrix} \alpha \\ \beta \end{bmatrix} = M^{-1} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix} = \begin{bmatrix} 1/2 & -1/2 \\ 1/2 & 1/2 \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix}. \tag{7}$$

This form also facilitates the calculation of an estimated uncertainty based on a quadratic propagation of standard uncertainties on the indications since M^{-1} is equivalent to

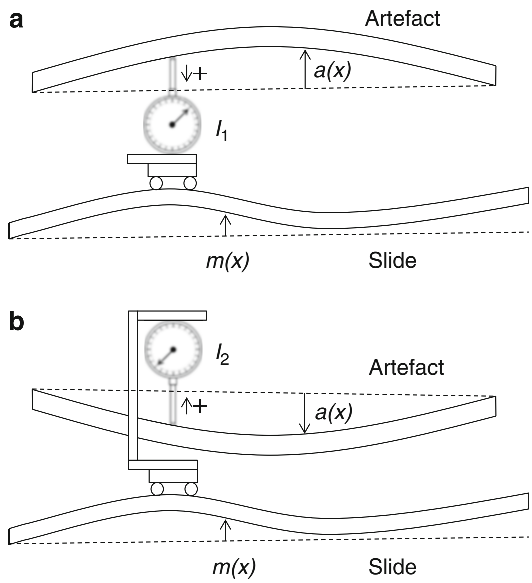
$$M^{-1} = \begin{bmatrix} \frac{\partial \alpha}{\partial I_1} & \frac{\partial \alpha}{\partial I_2} \\ \frac{\partial \beta}{\partial I_1} & \frac{\partial \beta}{\partial I_2} \end{bmatrix}. \tag{8}$$

According to the Guide to the Evaluation of Uncertainty in Measurement, the GUM (JCGM 102:2011 2011), since the measurement model has multiple inputs and multiple outputs, the covariances should be considered and so the uncertainty can be estimated as follows:

$$U_{\alpha\beta} = C_I U_I C_I{}^T \tag{9}$$

where $U_{\alpha\beta}$ is the covariance matrix of the output quantities (α and β), U_I is the covariance matrix of the input quantities (the level's indications), and C_I is the sensitivity matrix. They have the following form:

$$U_{\alpha\beta} = \begin{bmatrix} u(\alpha,\alpha) & u(\alpha,\beta) \\ u(\beta,\alpha) & u(\beta,\beta) \end{bmatrix},\ C_I = M^{-1} \text{ and } U_I = \begin{bmatrix} u(I_1,I_1) & u(I_1,I_2) \\ u(I_2,I_1) & u(I_2,I_2) \end{bmatrix}. \tag{10}$$



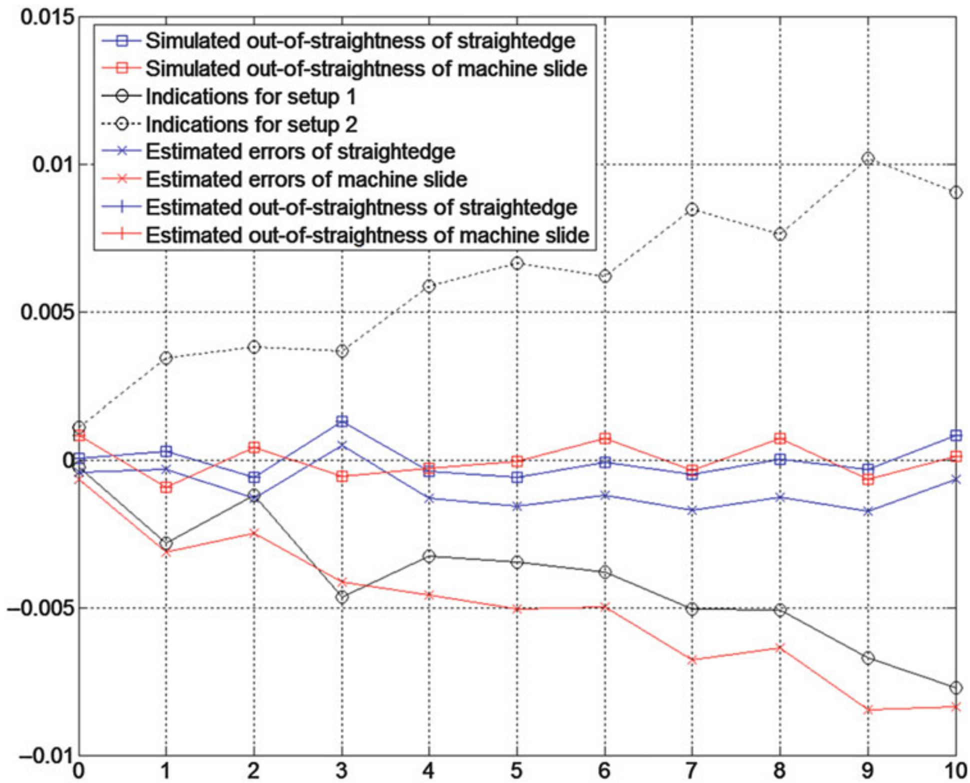
Reversal, Fig. 2 Straightedge reversal: (**a**) setup 1 and (**b**) setup 2 where the artifact is rotated by 180° around the axis of motion of the slide (reflection). Note that the sensor is also rotated which reverses the sense of the reading

Straightedge Reversal Method for Measurement of Straightness Error Motion

Straightedge reversal consists in using an artifact in the form of a straightedge to measure the imperfect motion of a nominally rectilinear displacement produced by a slide. The error motion varies along the slide. Figure 2 shows the two setups. Note that for the sake of simplicity the effect of pitch error motion is assumed negligible in the analysis that follows. Setup 2 results from a rotation of the artifact around an axis parallel to the direction of motion of the slide. The sensor is also rotated. The indication changes positively when the stylus enters the indicator body.

The indications, I_1(x) and I_2(x) for setups 1 and 2, respectively, are related to the artifact $a(x)$ and motion out of straightnesses $m(x)$ as follows:

$$\begin{aligned} I_1(x) &= -a(x) + m(x) \\ I_2(x) &= -a(x) - m(x) \\ \frac{I_1(x) - I_2(x)}{2} &= m(x) \\ \frac{I_1(x) + I_2(x)}{-2} &= a(x). \end{aligned} \tag{11}$$



Reversal, Fig. 3 Straightedge reversal simulation where random errors have been simulated on the slide and artifact. Reversal procedure is conducted with setup errors and a least square line is fitted through the estimated errors in order to obtain the estimated out-of-straightness errors

In practice a number of discrete measurement positions are taken along X at x_i, $i = 1, n$. At least $n = 3$ measurements are needed in order to have an out-of-straightness deviation because two points uniquely define a straight line and no point deviates from it so there is no out of straightness. The following system results:

$$\begin{bmatrix} I_{1,1} \\ I_{2,1} \\ I_{3,1} \\ I_{1,2} \\ I_{2,2} \\ I_{3,2} \end{bmatrix} = \begin{bmatrix} -1 & 0 & 0 & 1 & 0 & 0 \\ 0 & -1 & 0 & 0 & 1 & 0 \\ 0 & 0 & -1 & 0 & 0 & 1 \\ -1 & 0 & 0 & -1 & 0 & 0 \\ 0 & -1 & 0 & 0 & -1 & 0 \\ 0 & 0 & -1 & 0 & 0 & -1 \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ m_1 \\ m_2 \\ m_3 \end{bmatrix} \quad (12)$$

where $I_{i,j}$ is the indication at position i for setup j. Note the numerically convenient structure of the matrix as four 3×3 identity (positive or negative) matrices. A solution is again accessible, in principle, through a matrix inversion

$$\boldsymbol{I} = \boldsymbol{MA} \quad (13)$$

$$A = \boldsymbol{M}^{+}\boldsymbol{I}. \quad (14)$$

The condition number of $\boldsymbol{M}$ is $\kappa = 1$, again an ideal situation. The estimation results will be influenced by the setup of the artifact which injects an offset and a slope in the indications which will in turn corrupt the a and m values. However, since the straightness deviations are defined relative to a reference straight line (ISO 230-1:2012(E)), a further treatment is required on the estimated results. One possibility is to use the residual, $m'(x)$, from a linear regression through the estimated $m(x)$ values:

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Reversal, Table 1 Non-exhaustive list of reversal techniques (mostly from Evans et al. 1996; see also Hocken 2011 and Muralikrishnan and Raja 2009)

Reversal technique	Measurand	Artifact	Instrument	Reversal type
Level reversal	Surface inclination	None	Level	Rotation (180°) about local gravity line
Straightedge reversal	Out-of-straightness error motion of a linear axis	Straightedge	Dial indicator	Reflection of straightedge and indicator
Donaldson ball reversal	Spindle radial motion error	Ball	Dial indicator	Ball and indicator rotate (180°) about spindle axis
Square reversal	Out-of-squareness between two linear axes	Square	Dial indicator	Reflection
Estler's face motion reversal	Tilt and axial motion of spindle	Flat plate	Two dial indicators	Face and indicators rotation about spindle axis
Ball plate	XYZ machine geometry	Ball plate	Touch-trigger probe	Variety of rotations and flips

$$m' = m - \begin{bmatrix} x_1 & 1 \\ x_2 & 1 \\ x_3 & 1 \end{bmatrix} \begin{bmatrix} \text{slope} \\ \text{bias} \end{bmatrix} \qquad (15)$$

where the slope and bias can be estimated by solving the following system

$$\begin{bmatrix} m_1 \\ m_2 \\ m_3 \end{bmatrix} = \begin{bmatrix} x_1 & 1 \\ x_2 & 1 \\ x_3 & 1 \end{bmatrix} \begin{bmatrix} \text{slope} \\ \text{bias} \end{bmatrix} = X \begin{bmatrix} \text{slope} \\ \text{bias} \end{bmatrix} \qquad (16)$$

using the Moore-Penrose pseudo-inverse (symbol +) as follows

$$\begin{bmatrix} \text{slope} \\ \text{bias} \end{bmatrix} = X^+ \begin{bmatrix} m_1 \\ m_2 \\ m_3 \end{bmatrix} = \left(X^T X\right)^{-1} X^T \begin{bmatrix} m_1 \\ m_2 \\ m_3 \end{bmatrix}. \qquad (17)$$

Figure 3 shows the results of a simulation to illustrate this process. Out-of-straightness errors on both the machine slide and artifact are simulated using a random number generator. Then a setup error is added to the artifact position and orientation for both setups. The simulated out-of-straightness errors, the indications, the estimated errors from Eq. 14, and the out of straightness of those errors from Eq. 15 are also shown.

More Reversal

Table 1 is a list of some of the reversal methods found in the literature. More techniques can be found in the documents from the References section.

Cross-References

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

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Reverse Engineering

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Synonyms

Reverse modelling

Definition

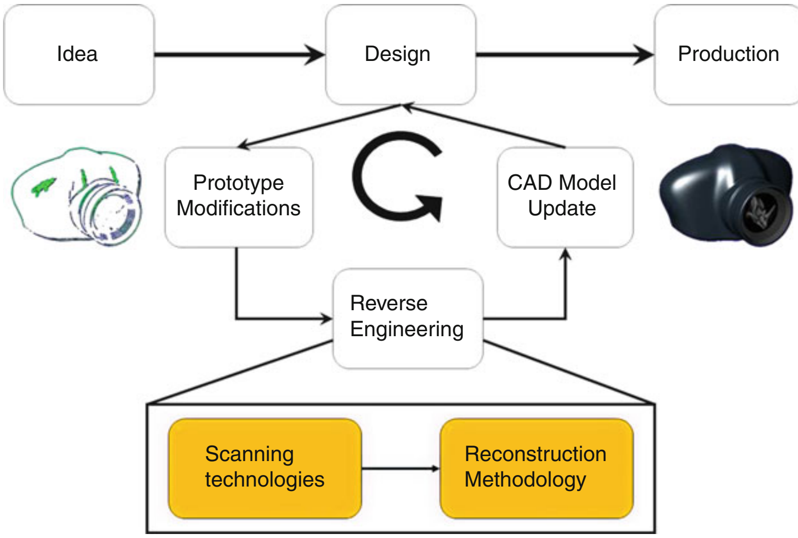
In Manufacturing Engineering and Industrial Design, Reverse Engineering is the process of achieving a 3D Computer-Aided Model of an existing object, starting from a point cloud obtained through a 3D digitizer or scanner.

Introduction

Reverse Engineering (RE) is used to acquire the model geometry and shape when product drawings are not available and/or component details have been modified, typically for *prototyping* purposes. This approach is divided into an acquisition phase to obtain a measured point cloud, through the direct 3D digitizing of the object, and an elaboration phase to rebuild the Computer-Aided Design (CAD) and/or a Solid-to-Layer (STL) model.

The choice of the appropriate 3D digitizing hardware depends on the required precision and the available scanning time. The output of these systems is a point cloud, a collection of measured data, organized into regular or scattered point sets. A triangulation operation is required to approximate scanned data into surfaces using triangular facets. A regular point set is functional to RE applications because it contains topological information about point connections. On the contrary, scattered data generated using manual point-wise sampling lack this information and cannot be directly interpreted. Moreover, the triangulation of scattered data requires the development and the application of specialized algorithms (Weimer and Warren 1999; Floater and Reimers 2001; Yu et al. 2010). The advantages of the RE approach are the immediate transfer of existing product data between divisions, rapid adaptability of CAD model to prototype changes (Fig. 1), and accurate measurements of the part geometry. The drawbacks are related to the difficulty of acquiring point clouds and to time-consuming operations required to process great amount of data and obtain the complete CAD model.

The amount of data needed depends on the required accuracy and on the product shape. A detailed point cloud is often required to allow the identification of all component features with an assigned accuracy. The elaboration task is time and effort consuming due to the large number of phases involved in the process of transforming this point cloud into other representations (surface, mesh, etc.). The experience of the user is crucial during the association between surface types and sub-point clouds, and the arrangement of the extracted surfaces. Moreover, the result of an RE application is a CAD model of the product only if further modifications are needed or in specific cases, such as finite element analysis, modal analysis, etc. In many cases, an STL file is sufficient, since it is a common file format for the product data exchange used for several engineering applications.



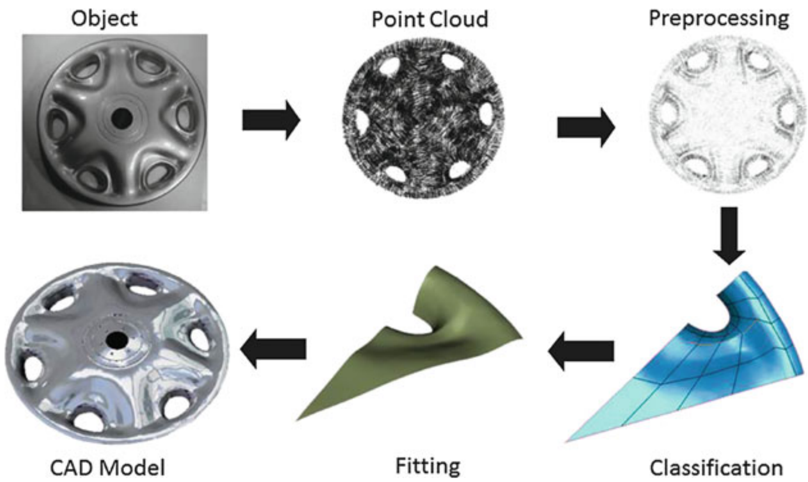
Reverse Engineering, Fig. 1 Integration between RE and prototyping

Hardware: 3D Digitizing Systems

3D digitizing hardware can be classified into tactile and non-tactile (Várady et al. 1997) methods, but nowadays non-tactile methods are the most widely spread.

An important kind of classification among non-contact data acquisition methodologies, using optical technologies is given below. They can be divided into different categories of technical solutions.

1. 3D Scanners: All 3D digitization systems based on moving emitters and receivers fall into this category. Image acquisition is possible through one or a number of laser or Infrared beams captured by mobile CCD cameras. These methods are quite expensive but, at the same time, very accurate. When information about a non-static object is required, there are some limitations due to the low speed of the acquisition method. The subject could unintentionally move during acquisition, causing errors in the final 3D model.
2. 3D imaging systems based on the projection of structured light (phase measurement profilometry) or on the analysis of Moiré fringes: These methods require the projection of light patterns over the face to be measured and the acquisition of the pattern image resulting from reflection on the given surface. The image, which is also acquired with CCD cameras in this case, must then be processed to determine the 3D point coordinates.
3. Instantaneous 3D imaging systems, based on photogrammetry: Complete 3D information is gained with the acquisition and matching of several images. The techniques based on photo realization can be distinguished according to the type and the number of images used. These methods are particularly suited to the digitization of human body data because of their insensitivity to slight body movements. Photogrammetry specifies the techniques, which assess the position, the shape, and the dimensions of an object starting from its photographs. The method allows measures to be made without any contact with the object and is based on the principle of triangulation. Photographs must be captured from at least two different positions and, using a plotted visual line from each camera toward the object, the intersection of these lines gives the 3D coordinate of the points of interest. When the distances are within 100 m, the method is called close-range photogrammetry. Over the past few years, industrial photogrammetry systems based on film cameras have become obsolescent since the introduction of digital close-range photogrammetric systems employing



Reverse Engineering, Fig. 2 Classical RE phases

high-resolution CCD sensors. The use of digital cameras allows immediate exploitation of the images acquired and simplifies the orientation process of the camera.

Software: Reconstruction Methodologies

Once the point cloud has been acquired, it generally requires the following operations (Fig. 2) which is performed spending high amount of time:

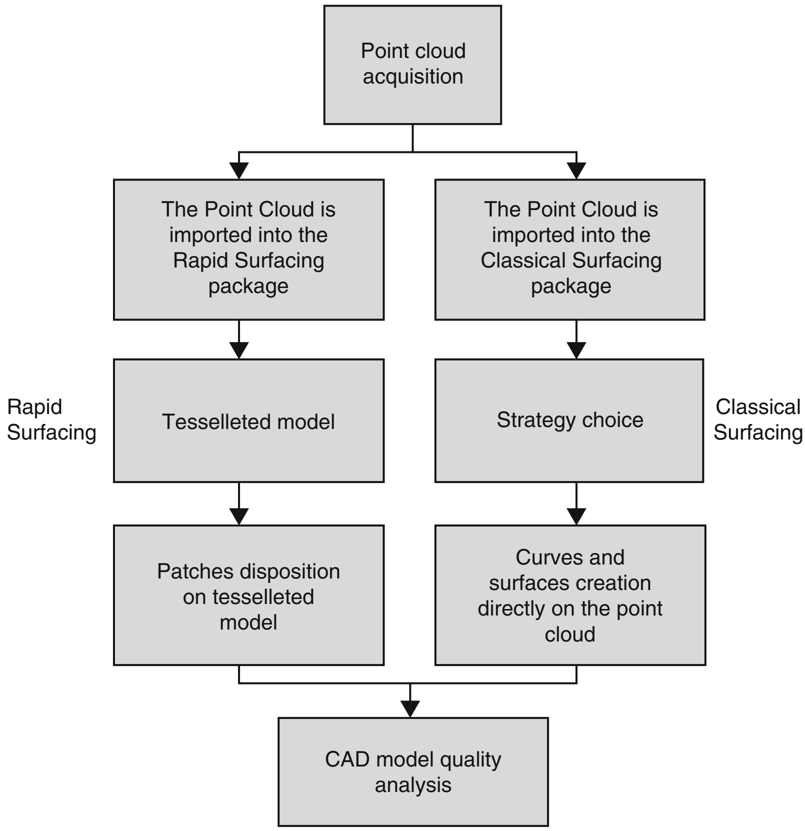
- Preprocessing: operations such as noise filtering, smoothing, merging, data reduction, and eventual tessellation before beginning the surface reconstruction process.
- Segmentation: the data set is divided into subsets creating a unique relation between each subset and a fitting surface.
- Classification: the information about the surface type for best fit is specified for each subset.
- Fitting: the surface that best approximates the selected subset is identified.

In recent years the surfacing software have undergone improvements and enhancements. The possibility of an accurate digital representation of any sketches is called classical surfacing. It is able to create high-quality surfaces, but great time investments and skilled operators are required, especially when high quality surfaces are needed. These disadvantages brought at the end of the 1990s to the development of the first “rapid surfacing” packages. These packages (Lecrivain et al. 2008), starting from a point cloud, create a polygonal mesh and then one or more surfaces are adapted to the mesh. Actually these software the most important on the market, classical surfacing is normally preferred when only general purpose CAD packages are available.

In Fig. 3 flowcharts of classical and rapid surfacing methodologies are shown.

Applications

Industrial applications are related to obtaining the 3D CAD model of existing components because the most intuitive method of process planning is the physical interaction with the model. In conjunction with rapid prototyping systems CAD models of new products can be quickly updated with modifications on prototypes proposed during the Concurrent Engineering process. Moreover, when the model is required to have particular aesthetical features, companies often employ artisans to realize wood or wax prototypes. Once the model is ready, it can be digitized and computer reconstructed. The digital model can be propagated to local engineers or to remote clients for a



Reverse Engineering, Fig. 3 Differences between rapid and classical surfacing methodologies

careful revision, or it can be used as reference as the realization of CAD models which can be modified for manufacturing.

Other reverse engineering applications are concerned with special effects, games, and Virtual World. These applications need models generated from reality and from models created by artists. Therefore, the digitization of physical objects becomes essential these virtual environments. In artworks applications, 3D digitizing can positively affect the cultural heritage safeguard in several fields such as (i) digital archives, (ii) replica of artworks, (iii) remote fruition, (iv) digital restoration, and (v) monitoring. Medical field applications are numerous: prostheses can be customized if the dimensions of the patient are known with notable precision. Plastic surgeons can use the form of the face of an individual to model a process of scanning of the fabric and to verify the results of the surgery. When radioactive treatments are performed, a model of the form of the patient can drive the doctor in the accurate direction of the radiations. Anthropometric studies that consider three-dimensional surfaces have been developed, deepening the analysis of 3-D geometries and morphologies of the major outer tissues of the human body.

Cross-References

▶ Product Development
▶ Prototyping

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Reverse Modelling

► Reverse Engineering

Robot

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Synonyms

Industrial robot; Manipulating industrial robot

Definition

The ISO definition of an industrial robot is: "An industrial robot is an automatically controlled, reprogrammable multipurpose manipulator programmable in three or more axes, which can either be fixed in place or mobile for use in industrial automation applications" (ISO 2012).

In the ISO definition, there is a differentiation of robots for industrial use and for other tasks useful to humans. A service robot is a robot that is used to perform all kinds of useful tasks for humans excluding industrial automation tasks. For that reason, the same robot can be classified as either an industrial robot when it is used for assembly or a service robot when it is used to serve food (ISO 2012).

History and Etymology of the Word Robot

The idea of creating machines that mimic human actions or behavior is old. Numerous attempts were made through the centuries to create "live" dolls or similar mechanical devices that could perform actions that were humanlike. The word robot though has a different origin. It comes the play R.U.R (Rossum's Universal Robots) written by the Czech author Karel Čapek. It was written in 1920; an English version of it was performed in New York in 1923 (Čapek 1923). In this play, the inventor Rossum has created humanlike "biological machines" that look and act exactly as human beings. They are called robots. The robots are made in factories and are used to do all kind of manual work required by humans. They do initially have no free will, no moral, and feel no pain. They obey all orders given by humans, even if it leads to self-destruction of the robots.

The word "robot" did not exist before it was introduced in R.U.R. It was proposed to Karel Čapek by his brother Josef as a name for the creatures he described in his play. Karel had other ideas for the name of the creatures, like "labori" and similar Slovak words, but he did not feel that they sounded well. Therefore he chose the word "robot" proposed by his brother.

In the online dictionary, Douglas Harper (2017) gives the following explanation of the meaning of the word robot:

> from English translation of 1920 play "R.U.R." ("Rossum's Universal Robots"), by Karel Capek (1890–1938), from Czech *robotnik* "slave," from *robota* "forced labor, compulsory service, drudgery," from *robotiti* "to work, drudge," from an Old Czech source akin to Old Church Slavonic *rabota* "servitude," from *rabu* "slave," from Old Slavic **orbu*-, from PIE **orbh*- "pass from one status to another" (see orphan).

After the introduction of robots as a concept in R.U.R., the science fiction literature adopted the robots as one of the main villains in future society. In most of this literature, robots were dangerous. It was only Isaac Asimov who created the idea of the good robot that served mankind. He formulated his three laws of robotics which stated that robots always should serve and never harm mankind and put protection of themselves next to that (Asimov 1964).

R

The first industrial robot was based on a patent for "Programmable Article Transfer" obtained by George Devol (1954). Devol and Joe Engelberger formed the company Unimation in 1956, and in 1959, this company presented its first machine, the Unimate. It was actuated by hydraulics and used as a magnetic drum for storage of positions that could be freely programmed by a teach pendant. The arm was spherical coordinate type; see Fig. 2b. The control did not offer linear path control, and all positions were given in local joint coordinates. The Unimate was first used industrially in 1961 in a GM plant in Trenton, NJ, USA (IFR 2012).

It is interesting to see that the name of the device patented by Devol was Programmable Article Transfer. There is no reference to "robot" in this name. Devol did probably not see his patent as something that resembled the robots in R.U.R. However, in the marketing of Unimate, the term robot was used. It probably led to a gradual acceptance of "robot" as the practical name for these automatically controlled manipulators.

In many European countries, there was skepticism toward the use of the term robot for automatic manipulators. This was probably due to fear that the general public would react negatively when "robots" were replacing workers in industry. For that reason, other names were used. In Germany, the term "Handhabungsgeräte" ("Handling devices") and "Industrieroboter" were used side by side up to the 1980s. This practice gradually changed. Today the official standard designation according to ISO is "industrial robot." In daily life, however, "robot" is used. Still the robots used in industry are clearly very different from the robots described in R.U.R.

In 1962, the company American Machine and Foundry (AMF) sold their first Versatran robot. This robot was of cylindrical coordinate type and thus a new development. Then in 1969, the Norwegian company Trallfa offered its first spray-painting robot (IFR 2012), an anthropomorphic robot using tape recording of the joint positions for continuous path control. The programming used a novel principle of teach in by leading the arm manually through the spray-painting operation in real time.

The first robot with all joints electromechanically driven was the Famulus introduced by the German Kuka company in 1973. In 1974, the Cincinnati Milacron robot T3 was the first robot to have a control system that offered full CNC type of linear path control. In decade 1970–1980, a number of manufacturers entered the scene, and the various types of industrial robots we see today were introduced. The last one in this line was the SCARA (Selective Compliance Assembly Robot Arm) developed by Hiroshi Makino in 1978 (IFR 2012).

Parallel leg robots appeared from several manufacturers in the 1980s. Although they offer some advantages, they have not obtained widespread acceptance. Still one variant, the FlexPicker introduced by ABB in 1998, has obtained a certain market due to its extreme high speed of operation.

Industrial Robot Classes

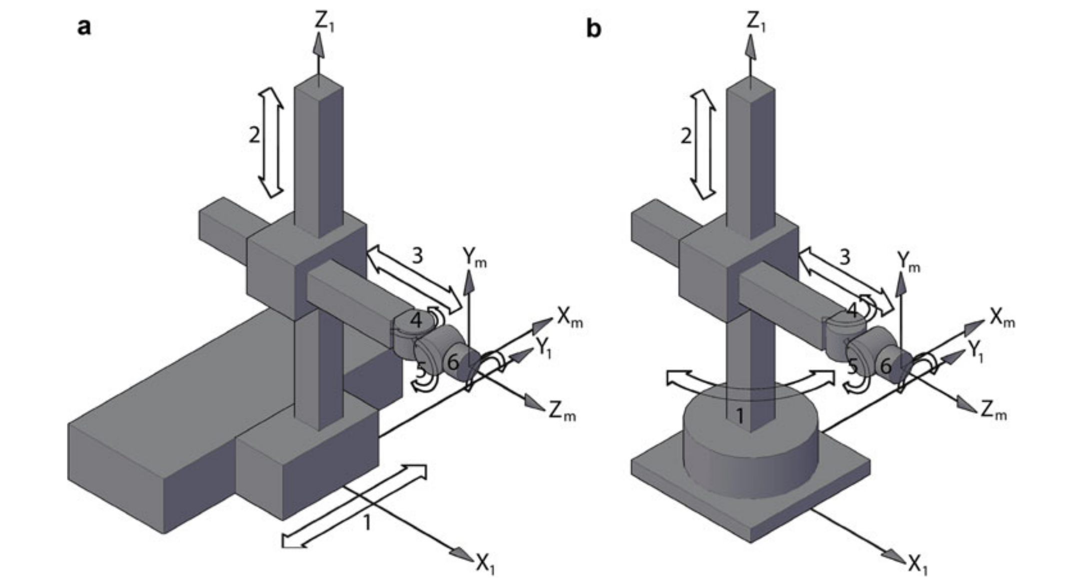
There are six basic classes of industrial robots characterized by the kinematic structure. Five of these are serial-type kinematic chains while the last one is a parallel leg structure.

Cartesian Robots

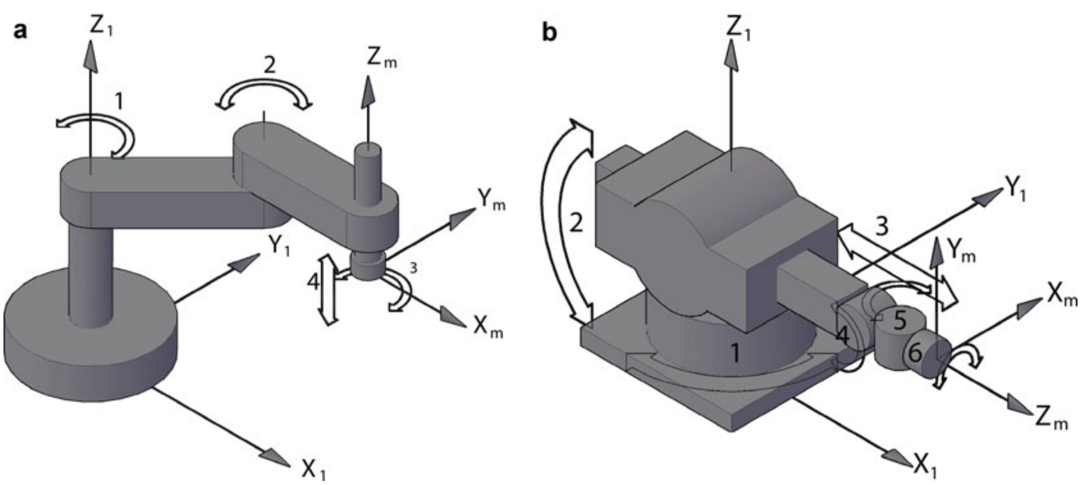
The Cartesian robot consists of three orthogonal linear links that comprise the arm and three rotational links that form the wrist system as shown in Fig. 1a. Cartesian robots are easy to control; the controller can be seen as very similar to a 6-axis machine tool CNC. Unlike all other robots, this type needs no coordinate transformations for linear motions. This makes the robot particularly suitable for linear movements where precise path control is required. The drawback of this class is the volume of its mechanical structure relative to the work volume it offers.

Cylindrical Coordinate Robots

Figure 1b shows the kinematic structure of cylindrical coordinate robots. The arm consists of two orthogonal linear links placed on a rotating base. In comparison to Cartesian robots, this configuration offers a larger work volume relative to the mechanical structure of the arm. The control system needed for linear path control relies on the solution of trigonometric equations which makes



Robot, Fig. 1 (**a**) Cartesian robot, (**b**) cylindrical coordinate robot

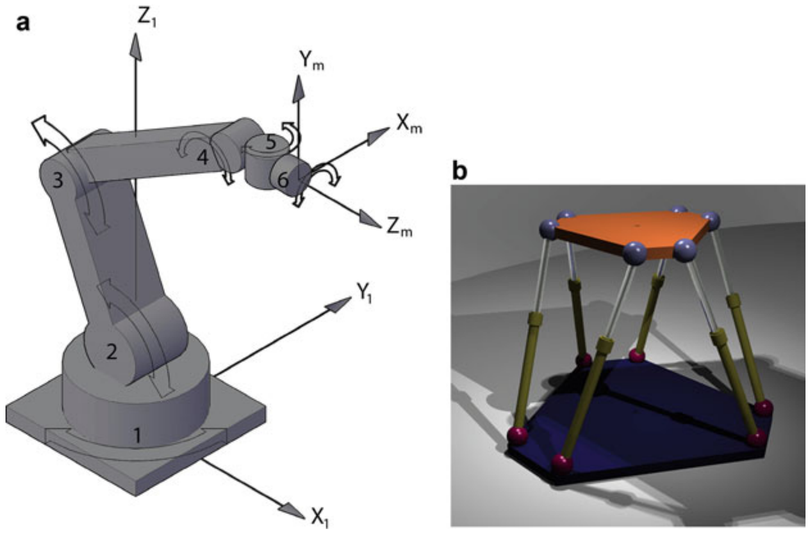


Robot, Fig. 2 (**a**) SCARA robot, (**b**) spherical coordinate robot

it slightly more complex than for the Cartesian robots.

SCARA Robots

The SCARA robot class, Fig. 2a, is a subclass of the cylindrical coordinate robots. It is still considered to be a separate class because of its unique properties. The name is an abbreviation of Selective Compliance Assembly Robot Arm. It was introduced as a robot for assembly tasks, and it is widely used for these and similar light operations in industry today (year 2017). Its unique feature is high vertical stiffness that enables the robot to perform very accurate vertical linear movements that makes it particularly suitable for assembly task. Some robots also offer a controllable horizontal compliance. This enhances vertical insertion with narrow tolerances where it is essential to avoid skewness of the vertical axis while using horizontal compliance for alignment.



Robot, Fig. 3 (**a**) Anthropomorphic robot, (**b**) parallel leg robot

Normally it has a limited wrist function offering only rotation of the end effector around the vertical axis.

Spherical Coordinate Robots

Figure 2b shows the structure of spherical coordinate robots. It offers a better ratio between work volume and mechanical structure volume than the cylindrical coordinate robot. But the dexterity is still much lower than that of the anthropomorphic robots. Since the complexity of control for this class is almost the same as for the anthropomorphic, it has almost completely vanished from industrial use.

Anthropomorphic Robots

The anthropomorphic robot, Fig. 3a, also called articulated robot, is the dominating class of industrial robots. Its kinematic structure is similar to that of the human arm; therefore, it is also the robot class that offers the best dexterity and the most humanlike behavior. The arm and wrist consist of a serial chain of links with rotational joints. This presents a complex control challenge for linear path control, but today's large capacity microcomputers have reduced this challenge to a manageable level. There are several variations of the kinematic structure for the wrist, while the three inner arm links normally have the same configuration for all robots in this class.

Parallel Leg Robot

The parallel leg robot is a system where three or six linear actuators in a tripod configuration move a platform that is the basis for either a wrist actuator structure or an end effector interface. In the three-legged variant, the platform is connected to the base via a spline shaft to prevent rotation and with a wrist element on the platform to obtain orientation capability. The six-legged variant, Fig. 3b, is also called Stewart platform or a hexapod. It obtains positioning and orientation by controlling the length of the six actuator legs. The parallel leg robot has the advantage of potentially very high stiffness in the direction perpendicular to its baseplate, making these robots particularly well suited for machining operations. The drawback is small workspace compared to other robots of similar size.

Theory and Application

Kinematics and Control of Industrial Robots

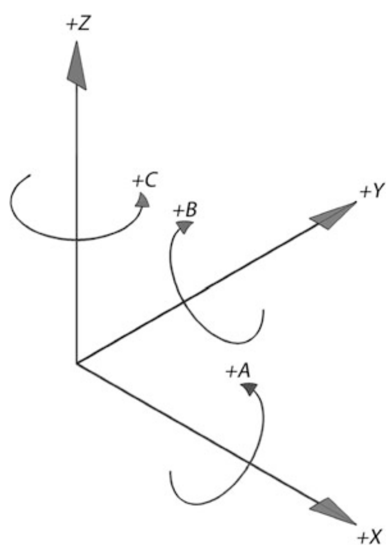
The control of industrial robots follows to a large degree the same principles as for machine tool CNC. The control program written by the user consists of data for path knot points; sequence of points to form the path, also called the trajectory; and velocity commands and commands for tool operation. There is no accepted standard robot control code or language. Each main manufacturer has its own programming language, but the general principles of robotic programming are similar across the field of robot programming languages.

Robot Coordinate Systems

All robots require geometrical specification of the operation in the robot's workspace. The international standard, ISO 9787 Robots and robotic devices – Coordinate systems and motion nomenclatures – defines how to specify positions and orientation of objects. It specifies that all coordinates should be defined in a right-hand Cartesian coordinate system with components of positions X, Y, and Z, while rotary motions around these axes are defined as A, B, and C. The positive A, B, and C rotations are in the directions to advance right-handed screws in the positive X, Y, and Z directions. This is indicated in Fig. 4 (ISO 2013).

The standard defines three essential coordinate systems as shown in Fig. 5:

- The world coordinate system C_0 is represented by X_0-Y_0-Z_0. This is the reference basis for all other coordinate systems used for a specific robot. The origin of this coordinate system is defined by the user and the $+Z_0$ points away from the center of the earth.
- The base coordinate system C_1 is represented by X_1-Y_1-Z_1. The origin of this system is in the center of the mechanical structure as defined by the robot manufacturer. The $+Z_0$ axis points into the robot structure away from the base mounting surface.
- The mechanical interface coordinate system C_m is represented by X_m-Y_m-Z_m. Here m= (the number of robot axes)+1. The direction of the $+Z_m$ axis is away from the mechanical tool interface as shown in Fig. 5.



Robot, Fig. 4 ISO definitions of axis directions and rotations for industrial robots (ISO 2013)

Many robot manufacturers do not follow the standard for C_m.

The Forward Coordinate Conversion

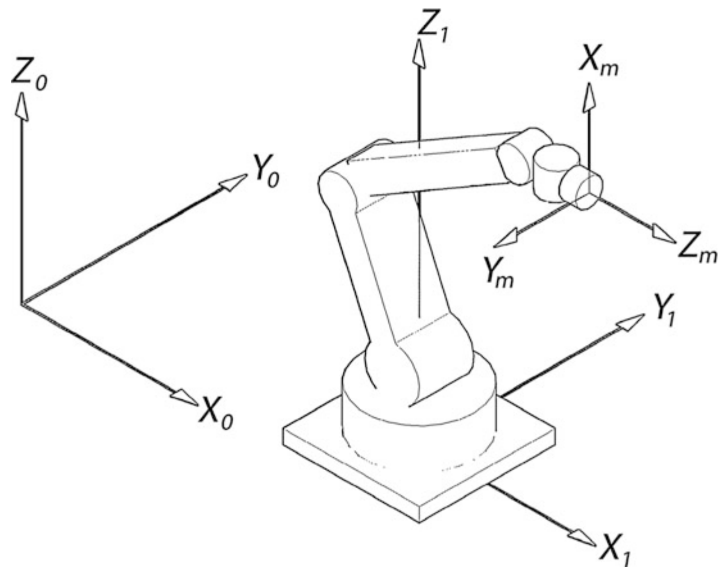
The main challenge of industrial robot control is the conversion into joint angles from path specifications given as Cartesian coordinates for pose according to ISO or similar Euler orientation coordinates. This challenge involves finding the inverse conversion from the pose vector $\vec{P}_p = \{X,Y,Z,A,B,C\}^T$ to the joint space vector $\overrightarrow{\Theta_p} = \{\Theta_1, \Theta_2, \Theta_3, \Theta_4, \Theta_5, \Theta_6\}^T$. To find the inverse conversion for a serial link robot, one has to start with the forward conversion function f_R (Lien 1979):

$$\overrightarrow{P_p} = f_R\left(\overrightarrow{\Theta_p}\right) \tag{1}$$

The forward conversion function f_R is found implicitly from the forward transformation T_p^m. This transformation is a homogeneous transformation between the arm end coordinate system C_m and the user program coordinate system C_p that normally coincides with C_1. This transformation converts the Cartesian coordinates $\vec{P}_m$, expressed in C_m, to $\vec{P}_p$, expressed in C_p (Lien 1979):

$$\vec{P}_p = T_p^m \vec{P}_m \tag{2}$$

The Cartesian coordinate vector in a homogeneous system is written as



Robot, Fig. 5 ISO definitions of coordinate systems for industrial robots (ISO 2013)

$$\vec{P}_i = \{x_i, y_i, z_i, 1\}^T \tag{3}$$

The general form of the homogeneous transformation between the coordinate systems C_i and C_{i-1} is

$$T_{i-1}^{i} = \begin{Bmatrix} r_{11,i} & r_{12,i} & r_{13,i} & x_i \\ r_{21,i} & r_{22,i} & r_{23,i} & y_i \\ r_{31,i} & r_{32,i} & r_{33,i} & z_i \\ 0 & 0 & 0 & 1 \end{Bmatrix} \tag{4}$$

Here the components x_i, y_i and z_i express the Cartesian distance from the origin of C_{i-1} to the origin of C_i. The rotational transformation matrix consisting of the components $r_{11,\,i}$ to $r_{33,\,i}$ are the directional cosines that express the projections of the position coordinates in C_i on the axes of C_{i-1} so that $x_{i-1} = x_i r_{11,\,i} + y_i r_{12,\,i} + z_i r_{13,\,i}$, $y_{i-1} = x_i r_{21,\,i} + y_i r_{22,\,i} + z_i r_{23,\,i}$, and $z_{i-1} = x_i r_{31,\,i} + y_i r_{32,\,i} + z_i r_{33,\,i}$ (Lien 1979).

The transformation T_{i-1}^{i} expresses the transformation of the coordinates of a point in the local coordinate system C_i to the coordinates of the next coordinate system C_{i-1}. By using this transformation recursively, a position expressed in C_m can be expressed in C_1 using Eq. 2 where T_p^m is:

$$T_p^m = T_p^1 T_1^2 \ldots T_{m-2}^{m-1} T_{m-1}^{m} \tag{5}$$

The x, y, and z components of T_p^m express the Cartesian distance from C_p to C_m. The orientation of C_m is derived from the rotational sub-matrix of T_p^m. The solution for this is depending on the type wrist structure and may not always be straightforward (Lien 1979).

The Inverse Coordinate Conversion

Finding the inverse conversion for serial link robots is more challenging. No one has yet presented a general solution for the inverse of Eq. 1. Nevertheless, it has been shown that there exist exact solutions for the inverse conversion for most of the six-axis anthropomorphic robots produced today. It is a requirement for such solutions to exist that the origin of C_m always will be at a constant normal distance from a plane, placed so that Z_1 lies in the plane and that the rotational axes of joints 2 and 3 are perpendicular to that plane. These closed-form solutions are based on geometrical analysis of the arm pose. They are also the most efficient solutions for the inverse conversion (Lien 1988).

If a closed-form solution cannot be found, an iterative method based on Newton-Raphson method may be used. This method works for all robots with six degrees of freedom. It is based on partial derivatives of Eq. 1:

$$d\vec{P}_p = \frac{\partial f_R\left(\vec{\Theta}_p\right)}{\partial \vec{\Theta}_p} d\vec{\Theta}_p \tag{6}$$

The partial derivative of f_R is called the Jacobean matrix J_R. The index R for this Jacobean indicates the specific robot studied. Using the Jacobean designation, Eq. 6 can be written as

$$d\vec{P}_p = J_R d\vec{\Theta}_p \tag{7}$$

By inverting this equation and replacing $d\vec{P}_p$ and $d\vec{\Theta}_p$ by $\Delta\vec{P}_p$ and $\Delta\vec{\Theta}_p$, an equation for approximation of a new pose by a differential motion from a known pose is obtained:

$$\Delta\vec{\Theta}_p = (J_R)^{-1}\Delta\vec{P}_p \tag{8}$$

Using this iteratively from a known pose and updating the obtained position by the forward conversion, f_R a successive approximation of the exact path to a programmed point can be obtained. It assumed that the initial pose is known. This is always is possible when f_R is known. This method is however more computational intensive than closed-form solution methods (Lien 1979).

The mathematics of forward and inverse conversion is the foundation of the complex field of robot control. This field includes trajectory planning and control, dynamics, and sensor signal interpretation. In this article, there is no room for detailed presentation of these themes. Many authors have covered these themes. A couple of textbooks that give good introductions and overview are *Introduction to Robotics* by John P. McKerrow (1991) and *Mechanics of Robotic Manipulation* by Matthew T. Mason (2001).

Kinematics of Parallel Robots

While it is easy to formulate the forward coordinate conversion for serial link robots, the opposite is true for parallel robots. There is no easy and straightforward solution known. However, the inverse conversion is easy to obtain. Liu, Fitzgerald, and Lewis have shown an elegant solution for the inverse conversion (Liu et al. 1993). They did also present an iterative solution for finding the forward conversion. Their solution uses the Newton-Raphson method to solve three simultaneous nonlinear equations. This is however a fairly computation-intensive approach.

However, from a control viewpoint, this state is not so bad. To control a specific parallel leg robot, it is sufficient to know the inverse conversion. It will give the required actuator length by direct solution of six simple equations for any pose of the end effector. Therefore the computational burden is moderate for practical operations of this type of robots.

Robot Sensory Systems

The basic control system of a robot controls its trajectory according to a preprogrammed path. This is sufficient for highly repetitive tasks as long as conditions directly related to the robot path do not change. But a large number of operations that can be automated by robots contain some sort of uncertainty. This requires individual observation of surrounding conditions or objects that shall be handled. Typical tasks are picking objects randomly positioned on conveyors or in containers, arc welding of parts with wide tolerances, grinding or polishing cast metal parts, or similar.

In all cases where conditions vary between operations, additional sensory systems are needed to enable automatic operations. The two most commonly used are electronic vision and force control systems. These systems connect to the robot controller through specific interfaces that enable handling of the additional sensory information with sufficient speed.

Vision systems enable both 2-D and 3-D objects recognition and pose determination. Two-dimensional picture analysis is state of the art and offers efficient solutions where 2-D information is sufficient for picking and placing of objects. Particularly in assembly, there are many tasks where 2-D imaging enables essential features relevant to the part assembly to be identified. For this reason, vision systems are natural parts of modern robotic assembly systems.

Still vision systems are not perfect. In particular, 2-D systems require that the objects to be recognized are seen in the same pose as presented to the vision system for initial image programming. Objects that have a few stable resting states only can be handled by multiple identification images. But objects with many different resting states present a larger problem. In addition the lighting of the object is crucial. Different light intensity can create differences in the images of an object so that they may not always be recognized by the vision system.

The application of force sensing offers challenges that are more complex. For simple tasks as stacking or picking from stacks, one-dimensional force sensing offers good solutions. Tasks like grinding and polishing of curved surfaces require a complex analysis of the grinding process that involves both material removal modeling for the given tool and workpiece combination and methods for measurement of the obtained surface dimensions after the operation. This area of sensor-based robotic operations is still under development.

Industrial Applications of Robotics

Modern industrial practice today is to apply robots wherever there are repetitive handling tasks. The purchase cost of one robot today (2017) is in the range of one to two times the yearly wage cost, including social costs, for a skilled industrial worker in most Western European countries, USA, Canada, and Japan. This means that one robot replacing one human operator in a two-shift operation will have a payback time in a year or less. In addition to the pure cost of operation, one or more of the following arguments will support the use of robots:

- Quality improvement: Industrial robots require higher quality level for input material and perform operations with less variance than human operators do. The experience from industry is that when the input material has less variance of dimension or other vital quality parameters, the output will also reflect this variance. In addition, poor input quality will lead to defective products in some cases. Improved input quality will mean no or lower number of defective output products.
- Workers' health issues: Robots can automate operations that are known to be harmful to manual workers' health, leading to less absenteeism in the staff.
- Reduction of throughput time: Automation with robots ties together operations to form short or long flow lines where the material flow rate is higher than in similar manual production.
- Flexible automation: The industrial robot is inherently very flexible. The use of robots enables the creation of potentially very flexible systems, both short-term flexibility through selection of movement programs from preprogrammed task libraries and reconfiguration by physical changes in surrounding support equipment.
- Attractive work places: The use of robots and similar modern automatic manufacturing equipment in computer-integrated manufacturing is attractive for highly skilled young people. This will ensure development of future competitiveness through a highly qualified staff.

The implementation of robotic solutions in industry is not without challenges. Some of these are:

- Redesigning of the manufacturing system layout. It is seldom the case that a robot can replace a human operator without any modification either to the machine(s) that shall be served or the surrounding equipment. This also includes building of safety fences and other devices needed for operator safety.
- Development of additional equipment for part feeding and retrieval from a robotic cell. In assembly, this is usually the largest cost factor and the more challenging part of the design of the robotic cell.
- Development of automatic supervision and product control system to take over process and product control tasks executed by manual operators before automation.
- Training of personnel to handle the complex tasks of programming, operating, and maintaining robots.

Typical areas of robotic applications in industry today are:

- Spot welding and arc welding on automobile assembly lines
- Spray painting
- Arc welding of complex small- to medium-sized components
- Arc welding of large ship elements by portable robots
- Part handling for standalone machine tools and in manufacturing cells
- Part handling in sheet metal forming
- Part handling in foundry operations, serving casting, and injection molding machines
- Grinding and de-burring of metal components
- Assembly of small- to medium-sized subassemblies in electronic, electromechanical, and mechanical manufacturing
- Packaging and palletizing in all types of industries

Cross-References

▶ Assembly
▶ Assembly Automation
▶ Computer-Integrated Manufacturing
▶ Computer Numerical Control
▶ Feeding
▶ Grinding
▶ Handling
▶ Manufacturing System
▶ Welding

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Rod Drawing

▶ Drawing (Wire, Tube)

Roll Forging

▶ Forge Rolling

Roll Levelling

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Synonyms

Straightening (for reduced number of rolls having bigger diameter)

R

Definition

In accordance to DIN 8586 (2003) "Manufacturing processes forming by bending – classification, subdivision, terms and definitions," roll levelling is classified as a bending process using rotating tool motion.

In more technological and industrial terms, roll levelling is the process where a sheet having flatness defects is straightened by imparting alternating bending operations using a set of bending rolls. The objective of the process is to minimize flatness imperfections and to level internal residual stresses of the material (Schuler 1998).

Theory and Application

Flatness Defects

During the hot and cold rolling of coils, work rolls are subjected to bending moments that produce heterogeneous plastic strains and thicknesses along the width of the sheet. As a consequence, different fiber lengths are generated, and diverse shape defects appear in the resulting coils. Furthermore, besides the bending deformation of the work rolls, other process variables, such as non-homogeneous cooling, coil up, and impurities in the lattice of the material, play an important role during the generation of coil defects.

Most of the authors have classified those defects depending on whether they are caused by a heterogeneous stress distribution through the thickness or through the width (Bräutigam and Becker 2009; Mathieu 2011). In Fig. 1 the most typical coil defects are presented.

The metal industry has developed several methods and standards to measure the flatness of the coils (Müller et al. 2013). The DIN EN 10131 (2006) and DIN EN 10051 (2010) standards define the tolerances on dimensions and shape of cold-rolled flat products and hot-rolled strip and plate/sheet, respectively.

In industrial environments, the flatness measurement is traditionally also expressed in international units (Mathieu 2011). This unit relates the height and the length of a wave in a sheet (see Fig. 2) by the following formula:

Defect		Origin	Corrective action
Coil set		Plastic deformation caused by the bending action of the sheets to create coils	Adjust tilting (entry and exit roll gap) using parallel rolls
Cross bow		Plastic deformation arising during the winding process	Adjust tilting (entry and exit roll gap) using parallel rolls
Wavy edges		Defect appears due to rolling errors such as excessive rolling rolls flexion typically when processing high width and small thickness strips	Increase plastification at central back-up rolls (parallel rolls are not suitable to correct this error)
Central buckles			Increase plastification at edges back-up rolls (parallel rolls are not suitable to correct this error)
Torsion		Appears when large differences exist in the strip tension or from too little tension during the winding process	Use roll levellers with a high number (17-21) of rolls, tight pitch and high entry plastification
Camber		The origin is in the uneven cooling of the material over the width of the coil	Use roll levellers with a high number (17-21) of rolls

Roll Levelling, Fig. 1 Typical coil shape defects

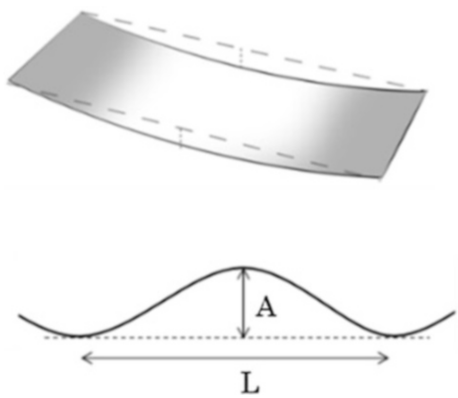
$$IU = \left(\frac{\pi}{2} \cdot \frac{A}{L}\right)^2 \cdot 100{,}000 \quad (1)$$

where A is the amplitude and L is the length of the measured wave.

Levelling Methods

Levelling is not a new process and exists since several dozens of years. Before the advent of modern levelling technologies for coil processing lines, bending presses using shims to support the sheet and to concentrate the applied load were used to level individual sheets (Fig. 3a). However, such a process was slow and inefficient, requiring a different bending strategy and sequence for each flatness defect, and residual stresses were present after the flattening operations.

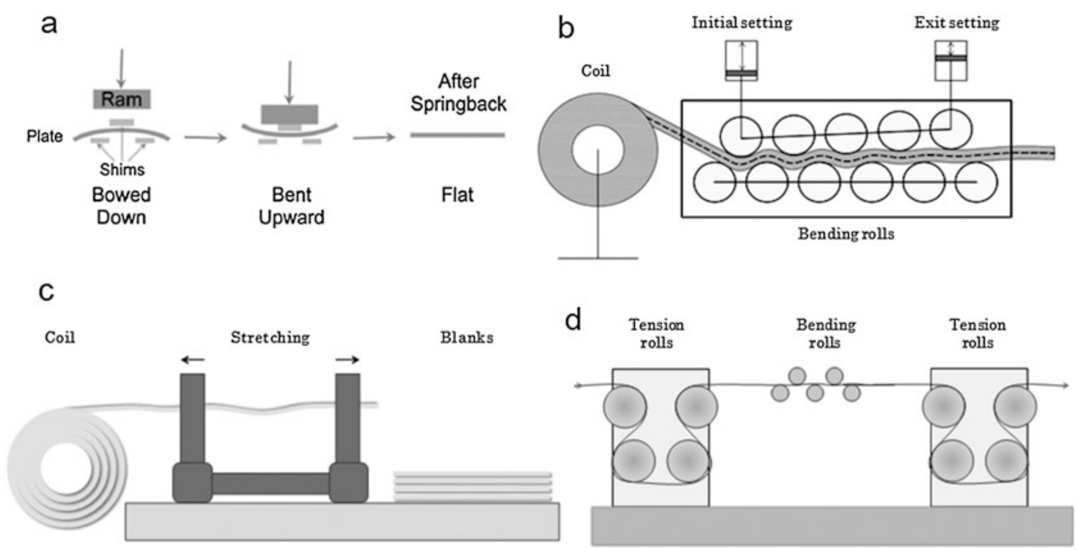
Currently, three different industrial technologies are used to level metal strips and coils. The roll levelling (Fig. 3b), described in this essay, is the most widely used method due to the low cost of the industrial facilities and the high processing speeds. The stretch levelling is used to non-continuously level high-thickness hot-rolled coils and strips (Fig. 3c). During the process, the metal strip is fully stretched by the use of two clamps so that, theoretically, no through-thickness residual stress is present after the process. The tension levelling is commonly used for levelling thin cold-rolled materials (Fig. 3d). During the process, S-type tension rolls are used to stretch the material, while a reduced amount of bending rolls create an extra plastification of the coil. As in the stretch levelling technology, 100% of the thickness is plastified using this technology.



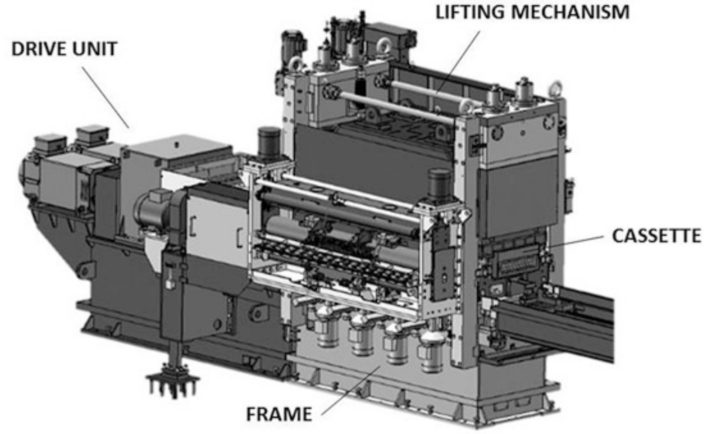
Roll Levelling, Fig. 2 Flatness measurement

Roll Levelling Machines

A roll leveller consists of four main parts (Fig. 4). The active part of a roll leveller is known as the



Roll Levelling, Fig. 3 Levelling technologies. (**a**) press levelling, (**b**) roll levelling, (**c**) stretch levelling, and (**d**) tension levelling



Roll Levelling, Fig. 4 Roll levelling machine. (Courtesy of FAGOR ARRASATE)

cassette. Generally speaking, it comprises an upper and a lower row of straightening rolls with the same diameter. The rollers in the upper row are generally arranged precisely above the gaps between the rollers of the bottom row. The distance between roll centers is known as the roller pitch (p) and varies in different machines, as does the roller radius (R) and the number of straightening rolls (Silvestre 2015). Different cassettes are commonly used in the same leveller to process different thickness materials. A cassette for precision levelling of thin coils with intermediate rolls is shown in Fig. 5.

The drive unit, typically placed in the back of the machine, includes the motor and reducer and the gearbox, where the motor motion is derived to the different working axis and the shafts connecting the gearbox with the levelling rolls.

The leveller frame absorbs the vertical forces and is normally constructed in a gantry-type design. The lower bed, the two uprights, and the crown form the frame of the machine. In conventional machines, the cylinders to vertically move the backup rolls are introduced in the bed of the machine and are used for the selective deflection of the levelling rolls.

The lifting or elevation mechanism is integrated in the crown to allow modification of the rolling gap. Although individual adjustment of the rolls is possible using hydraulic actuators, typically the whole row of upper rolls is vertically moved and rotated using spindles to obtain a progressively increasing rolling gap configuration.

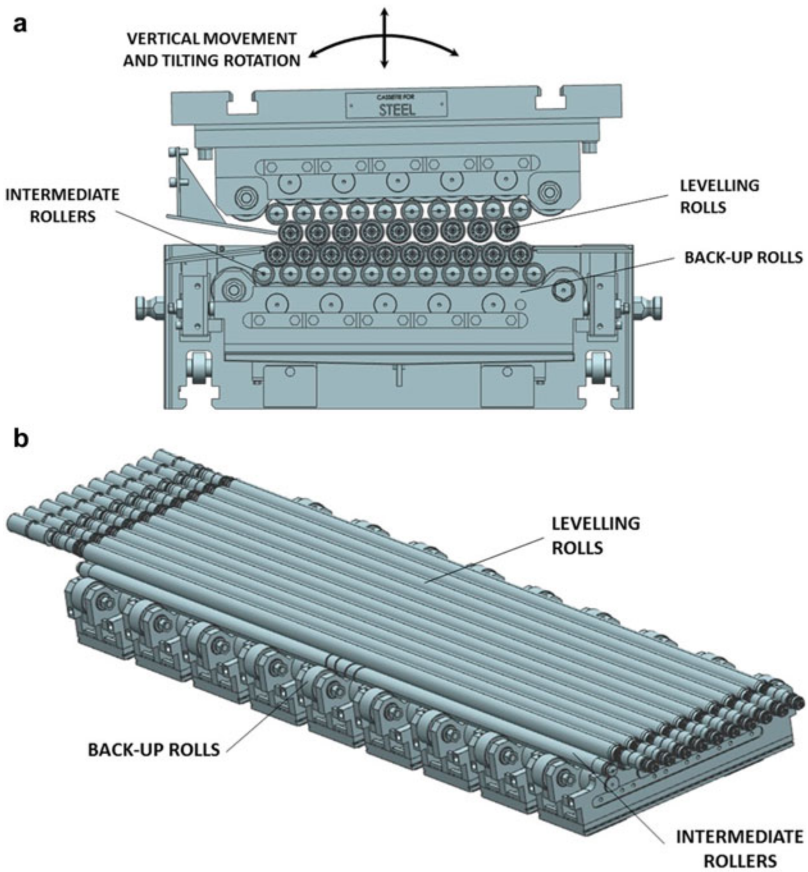
Roll Levelling Principle

As mentioned before, in roll levellers the metal strip is subjected to alternating bends. As it can be observed in Fig. 5a, the depth of the bends continually decreases in size as the sheets run through the machine from the inlet to the outlet. For that, the roll penetration or adjustment at the entry of the leveller (z) is higher than the exit.

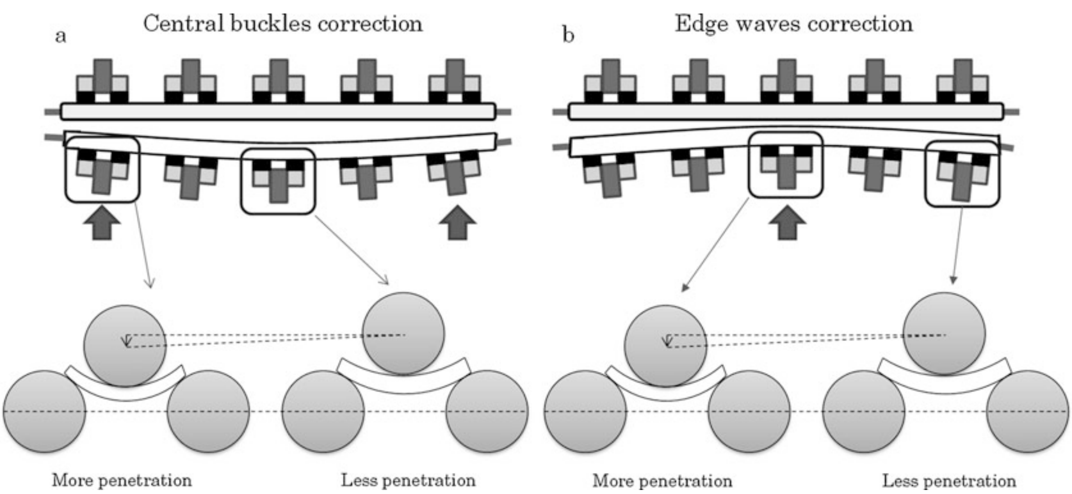
In the first working rolls, approximately corresponding to the first five rolls, in-width stress profile is homogenized. Plastic straining of the longitudinal fibers along the coil width removes typical defects such as coil set and crossbow. To effectively remove local defects such as central buckles or edge waves, a selective deflection of the levelling rolls is performed vertically moving the backup rolls so that the flat areas of the coil suffer more stretching and end with the same length of the wavy fibers (Semiatin et al. 2006). Typical backup rolls arrangements to remove central buckles and edge waves are shown in Fig. 6.

However, due to the strong bends in the first rolls, a pronounced through-thickness stress profile is generated. The aim of the subsequent rolls is to gradually reduce this stress profile so that a homogeneous narrow stress profile is obtained at the end of the leveller. Five straightening rollers are sufficient to level thick plates or coils or where no special demands are made on straightening accuracy. Where thinner materials or more stringent levelling requirements are involved, for example, for fine blanking or laser cutting,

Roll Levelling, Fig. 5 Layout of a precision leveller with intermediate rolls. (**a**) Front view. (**b**) Detail showing arrangement of backup rolls. (Courtesy of FAGOR ARRASATE)



R



Roll Levelling, Fig. 6 Backup rolls arrangement to remove central buckles (**a**) and edge waves (**b**) machines with up to 21 rollers are used. Commonly the exit penetration value corresponds to the sheet metal thickness and is adjusted to obtain a completely flat coil at machine exit.

It is industrially demonstrated that for a good levelling quality, a minimum of 70–80% of the thickness must be plastified in the first rolls. This maximum straining of the material is obtained by the first three fully effective levelling rolls, and normally peak strain along the machine corresponds to the third roll in the machine. Thus, the penetration or roll gap at the third roll is first calculated to then obtain the second roll gap, also called as entry value, which is of a relevant importance for a proper levelling of the material.

Considering plane strain conditions and the bending theory for high bending radius to thickness ratios (see "▶ Bending (Sheets)" entry), it is easily obtained that the bending strain at a certain fiber of the bend is

$$\varepsilon_b = \frac{y}{\rho} \tag{2}$$

where y is the distance from the neutral fiber to the analyzed fiber and ρ is the current bending radius of the neutral fiber (see Fig. 7).

Assuming a lineal through-thickness strain profile and using Hooke's law, the bending radius causing the yielding (ρ_y) of a given thickness percentage (e.g., pr, 80%) can be calculated by the following equation:

$$\rho_y = \frac{E' \cdot t \cdot (100 - \text{pr})}{2 \cdot \sigma_1 \cdot 100} \tag{3}$$

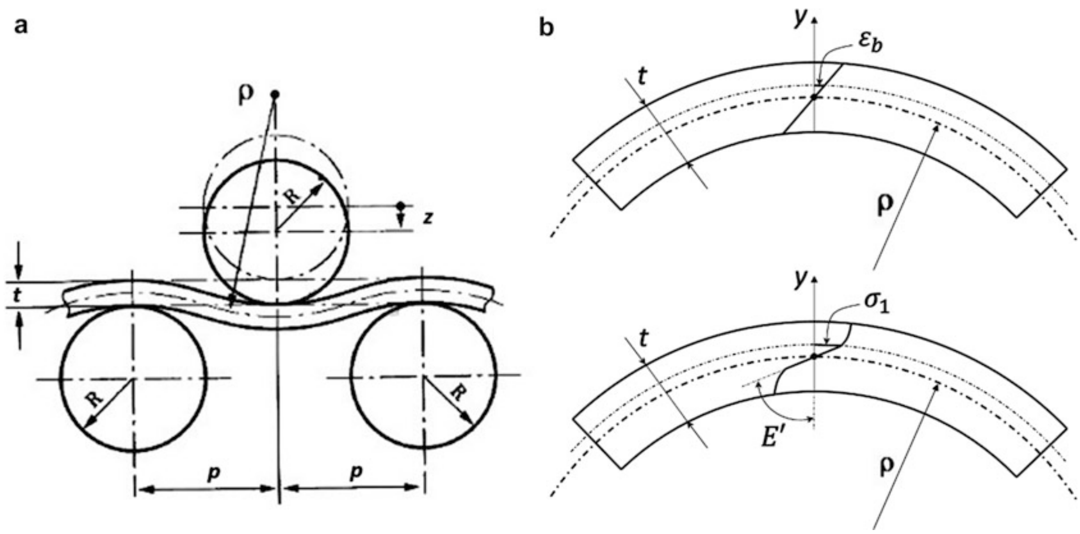
where E' is the modulus of elasticity in plane strain given by Eq. 4 and σ_1 is the plane strain yield stress given by Eq. 5 if von Mises yield criteria are assumed (Hu et al. 2002).

$$E' = \frac{E}{1 - \vartheta^2} \tag{4}$$

$$\sigma_1 = \frac{2}{\sqrt{3}} \cdot YS \tag{5}$$

where E is the uniaxial modulus of elasticity, ϑ is the Poisson's ratio, and YS is the uniaxial yield stress of the material.

From geometrical calculations, the equivalent roll penetration or adjustment causing this bending radius can be calculated as follows:



Roll Levelling, Fig. 7 (**a**) Schematic view of first three fully effective levelling rolls (**a**) and (**b**) stress and strain components in bending

$$z_3 = 2 \cdot \rho_y - \sqrt{4 \cdot \rho_y^2 - \left(\frac{t}{2}\right)^2} \quad (6)$$

The maximum roll penetration (z_{max}) is however defined by the upper and bottom rolls geometrical collision and can be calculated for a given material thickness using Eq. 7.

$$z_{max} = 2R + t - \sqrt{(2R + t)^2 - \left(\frac{p}{2}\right)^2} \quad (7)$$

where R is the roll radius, t is the material thickness, and p is the roll pitch.

Process Limitations and Levelling Window

The proper working of a roll leveller highly depends on the correct selection of the roll diameter, the roll pitch, the number of rolls, and the entry and exit penetration or adjustment values. These design parameters: the maximum available drive power and the maximum vertical levelling force, going to the machine frame, define the limits of a specific roll leveller to process a coil.

A typical limit processing window, called as levelling window, is shown in Fig. 8. This diagram represents a levelling process window which is the result of the intersection of three different limiting curves. Levelling operations below the limit curve are possible with the studied machine design.

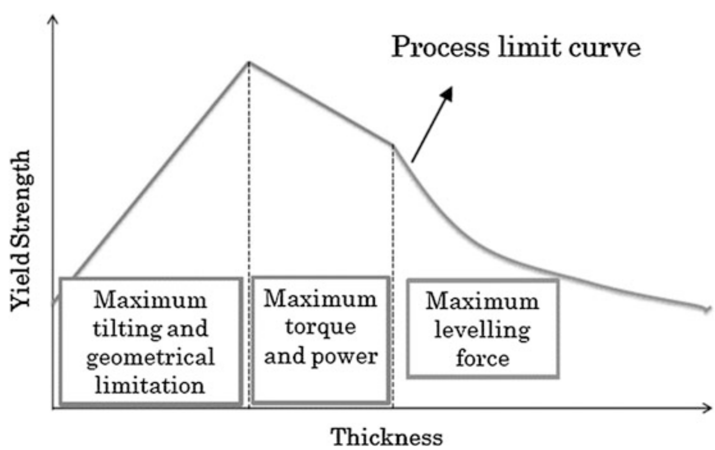
The left side of the window is limited by the maximum tilting or rotation capability of the leveller (the maximum allowed difference between the entry and exit penetration) and the maximum penetration of the rolls before physical collision obtained by Eq. 7.

The second part of the levelling window is limited by the maximum power/torque of the driving motor. The coil width and the yield stress of the material are the most affecting parameters, together with the thickness of the processed material.

The maximum vertical force the machine frame can support limits last part of the window, the right side. The thickness of the material together with the coil width and yield stress are the most affecting parameters for this limit.

The levelling forces and torques can be calculated using simple pure analytical or advanced semi-analytical models (Tselikov and Smirnov 1965; Doege et al. 2002). However, taking into account complex material behaviors, such as mixed kinematic hardening models, tribological behavior under different contact conditions, working speed influence, etc., is difficult when using these types of torque and force prediction methods. For that reason, different scientific papers have been recently published where finite element modeling (FEM) has been used to model and understand the levelling mechanism (e.g., Madej et al. 2011). Taking into account the mixed kinematic hardening models and considering a nonconstant friction coefficient have been recently demonstrated to be critical for roll levelling FEM optimization (Silvestre 2015).

R



Roll Levelling, Fig. 8 Example of levelling window

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▶ Bending (Sheets)

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Roller Bearing

▶ Bearing

Roll-Forming

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Synonyms

Profiling

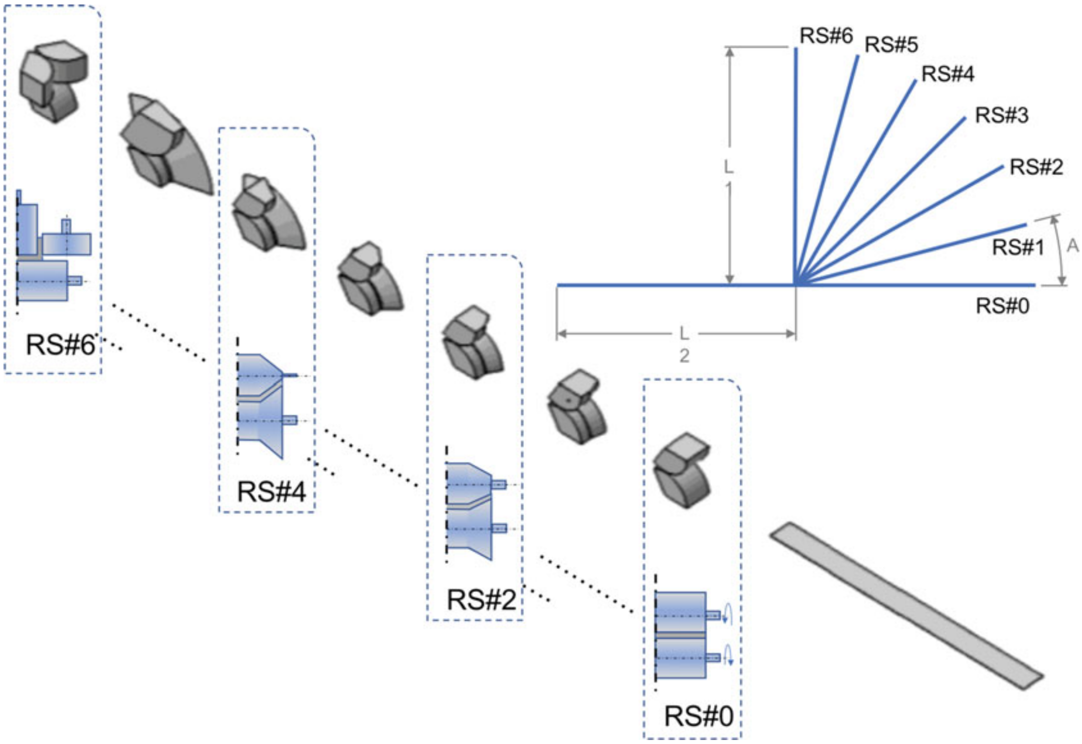
Definition

Cold roll-forming is a major forming process for the mass production of a variety of complex profiles from a wide spectrum of materials and thicknesses. According to Chryssolouris (2005) and Lange (1985), roll-forming process is classified into the category of sheet metal forming by bending with rotary tool motion. The plastic deformation of a solid body is achieved by means of a bending load. The metal strip enters into the roll-forming mill, in a precut or coil form, and it is gradually formed through consecutive contoured rolls into complex shapes (Fig. 1). Three-dimensional deformations of the material include transversal bending and other additive redundant deformations.

Theory and Application

Cold Roll-Forming Process Characteristics

Cold roll-forming process shows several key characteristics that make it rather competitive for

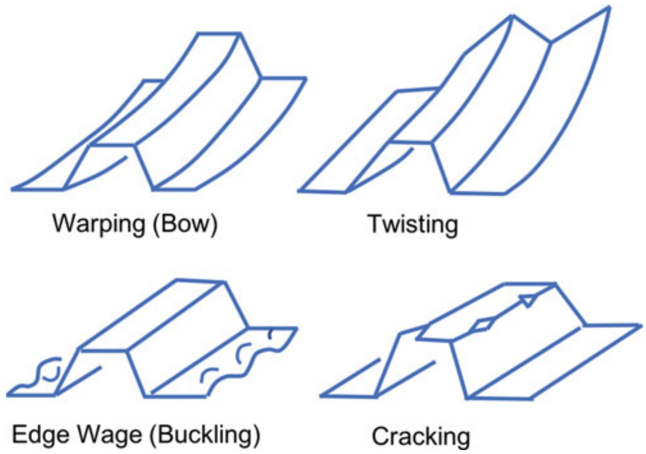


Roll-Forming, Fig. 1 Schematic of a cold roll-forming process (RS: Roll station)

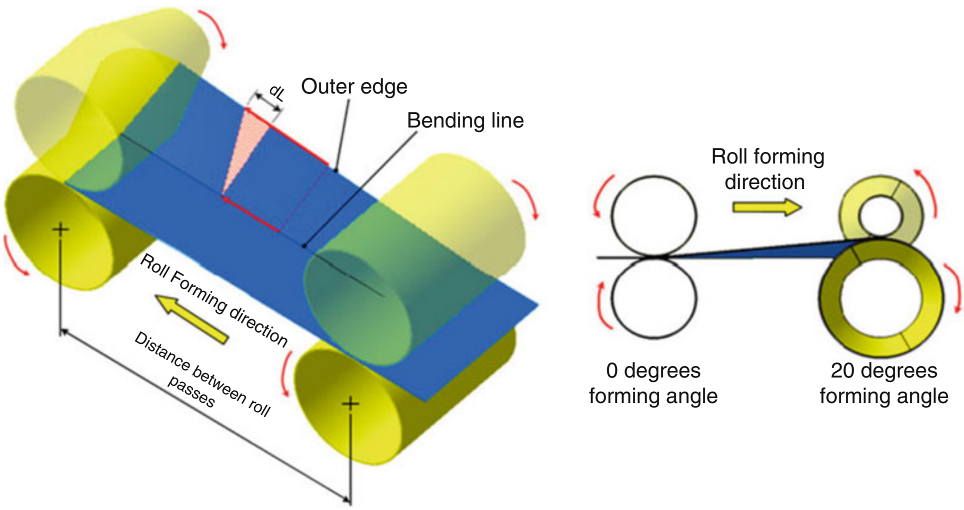
the mass production of straight profiles. It has low investment cost compared with other profiling processes, such as deep drawing. Its production speed can reach 30–60 m/min of produced profile, which makes it suitable for mass production. Tooling has low maintenance cost and provides very good dimensional stability of complex profiles. Roll-forming mills show flexibility in tooling changes and tooling adjustability with no cost and low setup times. Moreover profiles at any length can be produced with no additional cost (cut at length). On the other hand, only straight profiles can be produced with open ends, and experienced specialized engineers and designers are required for the production of very complex profiles.

Cold roll-forming main defects, such as bow, twist, edge waviness (buckling), and edge cracking, are caused mainly from redundant deformations (Fig. 2). These kinds of defects and quality characteristics are mainly affected by various types of deformations, namely, the transversal elongation and bending, longitudinal elongation and bending, as well as the shear in strip plane and thickness direction. The only desirable deformation for the bending of the profile is the transversal bending, while the others are characterized as redundant deformations and are responsible for the existence of main defects during the roll-forming process. The major redundant deformation is longitudinal strain, exhibited as stretching of material along flange. Longitudinal strains are produced at the flange, as the outer edge travels a greater distance than the web does through successive rollers (Paralikas et al. 2009; Fig. 3). Panton et al. (1996) have also discussed that both the longitudinal and the shear strains cannot be simultaneously minimized, but instead, a compromise between them should be achieved.

The main roll-forming process parameters include the roll-forming line speed, the roll station inter-distances, the existence of lubricant (friction coefficient), the roll gap, and the roll diameter. Using finite element analysis, Paralikas et al. (2009) modeled the effect of all these process



Roll-Forming, Fig. 2 Main defects caused by redundant deformations on roll-formed products. (Reproduced with permission from Springer, originally appeared in Paralikas et al. 2011)



Roll-Forming, Fig. 3 Outer edge travels greater distance than web through successive rollers. (Reproduced with permission from Springer, originally appeared in Paralikas et al. 2011)

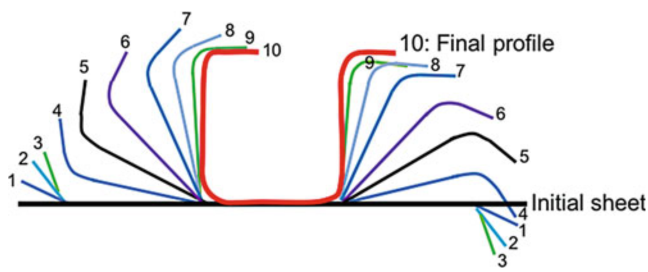
parameters on the total and elastic longitudinal strains at the strip edge along the roll-forming direction, as well as the distribution of longitudinal and transversal strains on the profile after exiting the final roll station. In Table 1, adapted from Paralikas et al. study, the effects of main roll-forming process parameters on longitudinal, transversal strains and dimensional accuracy of the profile after the final roll station are presented. The same authors, based on these findings, presented an optimization method for selecting the process parameters and designing the roll-forming stations (Paralikas et al. 2010) in order to produce profiles close to the drawings with minimized cost. The optimization can be further elaborated to account for energy efficiency of each station (Paralikas et al. 2013a, b).

Cold Roll-Forming Tools

Rolls are the tools that form the strip into the desired shape and turn it into roll-formed products. The design of the forming steps is called “flower pattern” and shows the subsequent bending of profile from one roll station to the other. Figure 4 shows the “flower patter” of

Roll-Forming, Table 1 Effects of main roll-forming process parameters on longitudinal, transversal strains and dimensional accuracy of the profile after the final roll station. (Reproduced with permission from Springer, originally appeared in Paralikas et al. 2009)

Effect on / Increase of	Longitudinal strain peak @ strip edge	Longitudinal residual strain @ strip edge	Dimensional accuracy	Transversal strain @ bending corner
Line velocity	😐	☹️	😐	☹️
Rolls inter-distance	🙂	🙂	😐	🙂
Friction coefficient	😐	☹️	😐	☹️
Rolls gap	🙂	☹️	☹️	☹️
Rolls diameter	😐	🙂	🙂	🙂



Roll-Forming, Fig. 4 Typical flower pattern for a roll-formed profile

a roll-formed profile, produced after ten consecutive contoured rolls.

Several factors have to be taken under consideration when designing the rolls that would form a particular product. These include the number of passes required, the material width, the flower pattern design, the roll design parameters, and the roll material (Wick et al. 1984). The number of passes required is estimated, based on material properties, thickness of the strip, and complexity of the profile to be produced (Wick et al. 1984; Halmos 2006). The strip width can be calculated from the profile drawing, based on the bend allowances calculated, the arc lengths of the curved elements, and the straight lengths of the shape (Alvarez 2006). The flower pattern design and orientation comprise the initial step of the roll tooling design and represent the designated flow of material into the mill, based on the number of passes required. The roll design parameters include the design of the rolls around each overlay of the flower pattern and the considerations for the diameter of the rolls as well as the desired tolerances (Halmos 2006; Paralikas et al. 2011).

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Materials to Be Processed with Cold Roll-Forming

Almost any material that can tolerate bending to a desired radius can be roll-formed. The more ductile a material is, the better it will roll-form. The roll-forming process can handle ferrous, nonferrous, hot-rolled, cold-rolled, polished, plated, or pre-painted metals producing excellent results.

Cold Roll-Forming Process Advantages

Roll-forming offers a number of distinct advantages over other metal-fabricating methods, such as:

- The initial cost of a roll-forming line is not exceeding the cost of a standard stamping line or progressive die operation.
- Production speeds of 15–150 m/min can be attained, but 30–60 m/min is a reasonable average for most current equipment.
- Roll-forming is a high-volume process that makes uniform and accurately dimensioned parts.
- Parts are produced with little handling, minimizing labor costs, needing only the coils to be loaded at the starting end of the machine and removal of finished parts at the other end. This process can usually be handled with a minimal number of operators.
- Roll-forming can also be used for low-volume production because setup or changeover time for new parts is not lengthy.
- Maintenance costs are generally low. The form rolls can produce several million meters of product before problems occur when properly maintained.
- The roll-forming process is easily combined with other operations and processes to automatically form a considerable range of metal parts.

Cold Roll-Forming Process Limitations

A few limitations also exist for cold roll-forming process, such as:

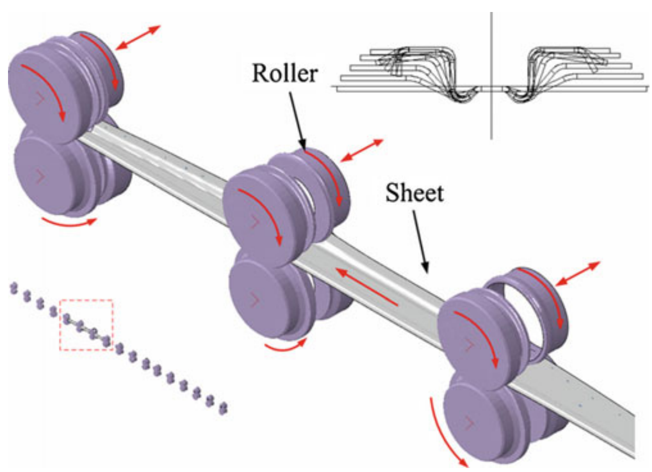
- Experienced roll design engineers must design those rolls for complex shape forming.
- Complicated tubular shapes, and some closed shapes, may need mandrels to form the shape accurately.
- Delicate, breakable, machine parts may need recurrent replacement during high-volume production runs.

Cold Roll-Forming Process Applications

Cold roll-forming, as a metal-fabricating process, is used in many diverse industries to produce a variety of shapes and products. Roll-forming is a desirable process since it adds both strength and rigidity to lightweight materials. Major industries using cold roll-forming products are automotive, aerospace, building construction, highway construction, furniture, home appliances, medical, marine, railways, etc.

Cold Roll-Forming Process Future

Cold roll-forming can produce in a cost-effective way continuous profiles with constant longitudinal cross section. This is the key advantage of the process, but also poses a limitation on where it can be applied. However, industry in many cases demand variable cross sections. A typical example is the automotive industry, where variable cross sections are widely used in the body in white. A roll-forming process variation is the flexible roll-forming process that can produce variable cross section profiles. In such a



Roll-Forming, Fig. 5 Flexible roll-forming process. (Reproduced with permission from Springer, originally appeared in Yan et al. 2014) process, instead of rigidly fixed rollers, they are translated back and forth in the width direction to form the variable cross section (Yan et al. 2014). An example of such a process is shown in Fig. 5.

Cross-References

- ▶ Bending (Sheets)
- ▶ Bending (Tubes, Profiles)
- ▶ Stretching

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Rolling

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Synonyms

Bonding; Caliber rolling; Deformation; Flat rolling; Flexible and strip profile rolling

Definition

Rolling is a process used to change the geometry of the produced material. Usually the cross section is reduced, and, as a result, the length increases.

Theory and Application

Rolling

The majority of all metals will undergo a rolling process during the production chain from metal casting to the final product, e.g., strips, blanks, profiles, etc. The respective rolling processes may be used to define the product geometry, material properties, or functional surface properties.

The main goals of flat rolling processes are the reduction of the cross section accompanied by the enlargement of the rolling stock length and the defined adjustment of material properties (e.g., yield strength or surface property) (Groover and Tonkay 2007).

A variety of rolling processes exists that lead to different final geometries and material properties. A brief overview of the most important rolling applications is given in this entry.

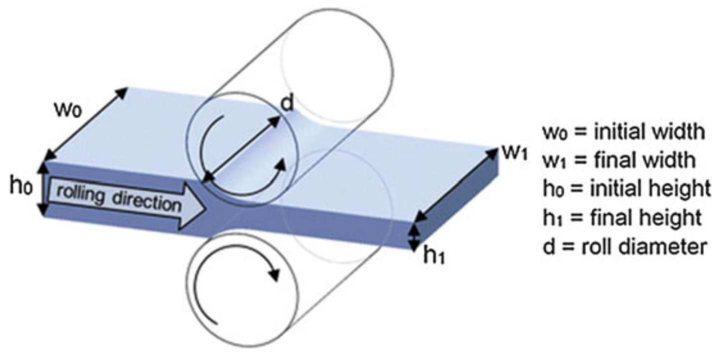
Flat Rolling

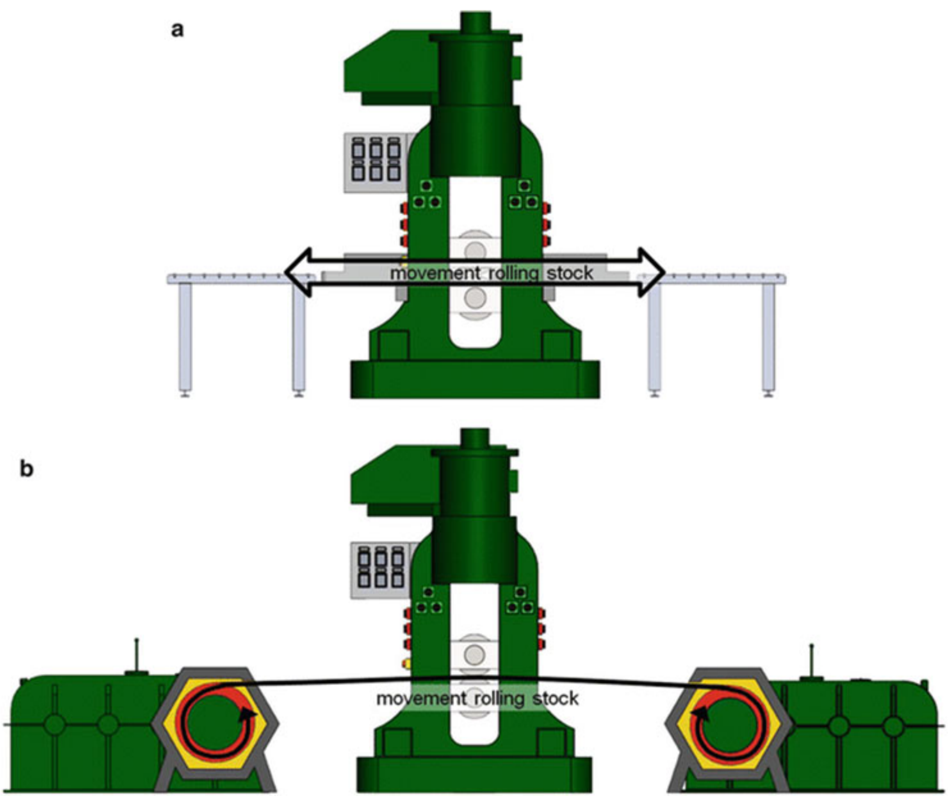
Rolling of flat products is the most important rolling process as the major portion of all metal produced is formed into flat products such as sheets and strips (Allwood et al. 2011).

Groover (Groover and Tonkay 2007) describes the flat rolling process as a forming process with cylindrical rolls and rolling stock with a rectangular cross section. In most cases, material flow is predominantly in rolling direction and spreading is avoided. This plane-strain deformation can usually be assumed if the width of the rolling stock is at least ten times greater than the thickness (w/h > 10). A sketch of a simplified rolling process and some geometrical parameters are shown in Fig. 1.

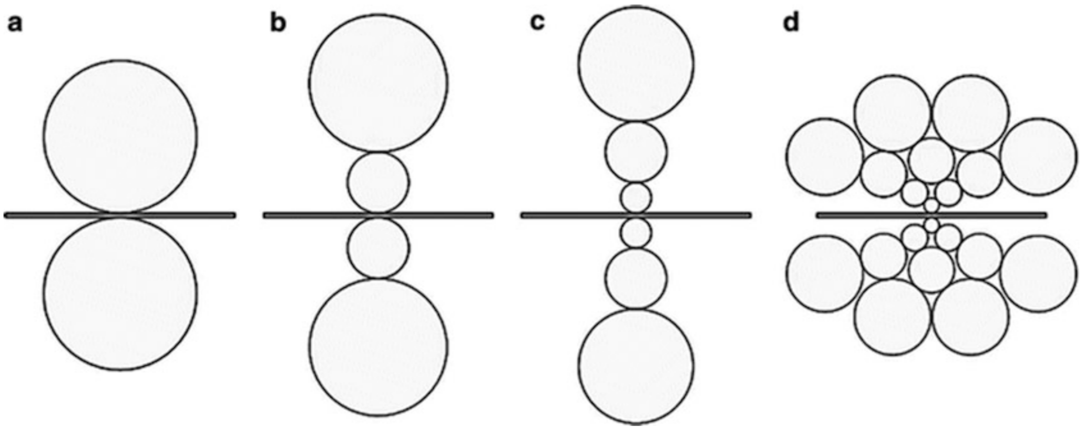
In most rolling processes, more than one rolling step is needed to achieve the desired final sheet geometry. One option is to roll the sheet in the same rolling mill changing the rolling gap for each step in a so-called single stand. In this case, usually the rolling direction changes each step. This procedure is called reverse rolling and is done with roller tables (Fig. 2a) or a Steckel mill (Fig. 2b).

Rolling, Fig. 1 Schematic rolling process with 2-high mill setup





Rolling, Fig. 2 Single-stand mill with roller tables (**a**) and a Steckel mill (**b**)



Rolling, Fig. 3 Different roll setups: 2-high mill (**a**), 4-high mill (**b**), 6-high mill (**c**), and cluster mill (Sendzimir) (**d**)

In addition to the 2-high mill setup that is illustrated in Figs. 1 and 2, there are several different kinds of rolling mills for flat rolling. The main variance is the size and number of rolls. Figure 3 shows some rolling mill setups. The setups result from the different applications, e.g., hot and cold rolling. The working roll diameter has a major influence on the rolling force. One way to reduce the rolling force is to decrease the roll diameter. As thinner rolls are more likely to deflect, backup rolls are used to prevent this. Otherwise, this would affect the flatness of the strip.

If the deflection of the rolls cannot be avoided by backup rolls, the strip becomes thinner from the center of the strip toward its edges. This can result in an inappropriate strip thickness, or if the thickness deviation gets big enough, this can result in undesired edge buckles. This effect can additionally be avoided by roll bending or the use of crowned rolls (Chiran et al. 2010).

As mentioned before, every roll setup has a typical application. For rolling processes with larger thickness reductions, e.g., hot rolling, bigger roll diameters are required to ensure that the rolling stock is drawn into the roll gap by friction forces. Taking this into account, 2-high mills are used in roughing stands where a high thickness reduction is intended, while the needed rolling forces are relatively small due to high temperature. 4-high mills are commonly used in hot strip rolling mills or heavy plate mills, but also in cold tandem mills. A 6-high mill setup is used in applications with relatively high rolling forces and processes where high precision according to the strip geometry is required, for example, electric steel. Cluster mills, like the Sendzimir setup in Fig. 3d, are used for high-strength steels and stainless steels.

Another very common option in contrast to the single-stand mill is the use of a tandem mill with up to seven consecutive rolling mills (Fig. 4).

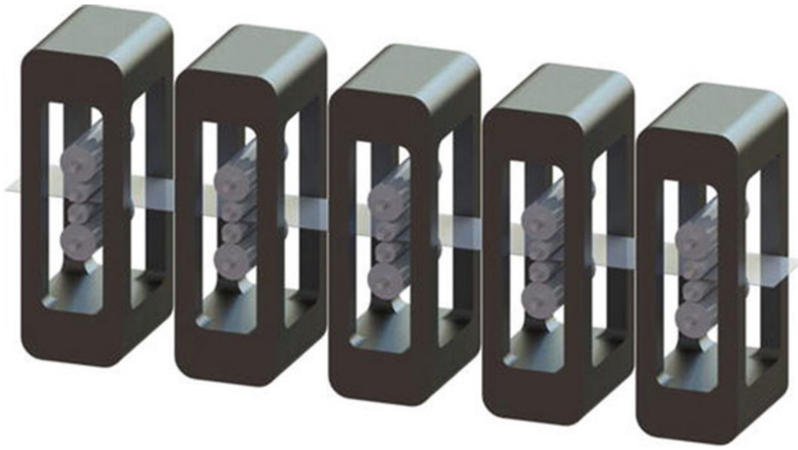
Analytical Equations

In general, the rolling process can be approximately described by a few analytical equations. Figure 5 shows a cross section of the rolling gap with the most relevant parameters. Geometrical parameters are the roll diameter d and radius r, the contact length l_c, the thickness reduction Δh, and the lever arm distance a of the force F. This distance depends on the distribution of the resulting pressure p_x.

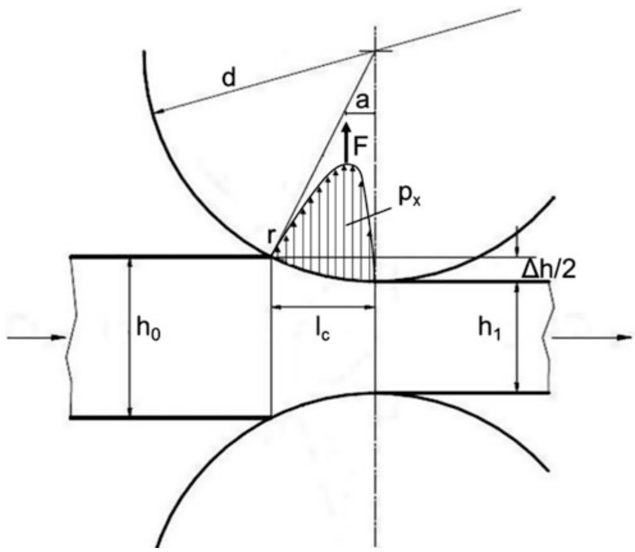
The contact length is important for the simplified calculation of the force. Based on geometric considerations, it can be described by Eq. 1:

$$l_c = \sqrt{r \cdot \Delta h - \frac{\Delta h^2}{4}} \approx \sqrt{r \cdot \Delta h} \tag{1}$$

Based on the slab theory (Siebel 1932), the rolling force F can be estimated by simplified equations. The basic idea is that the rolling force



Rolling, Fig. 4 Schematic 5-stand cold rolling tandem mill



Rolling, Fig. 5 Cross section of the roll gap

is the product of the contact surface (l_c*w) and the resistance to deformation, which results from flow stress and additional pressure required to overcome the influence of friction and shear effects.

For the friction-dominated range ($l_c/h_m > 1$), Eq. 2 by Siebel (1932) is a good approximation:

$$F = 1.15 \cdot w_m \cdot l_c \cdot \sigma_y \cdot \left(1 + \frac{1}{2} \cdot \mu \cdot \frac{l_c}{h_m}\right) \quad (2)$$

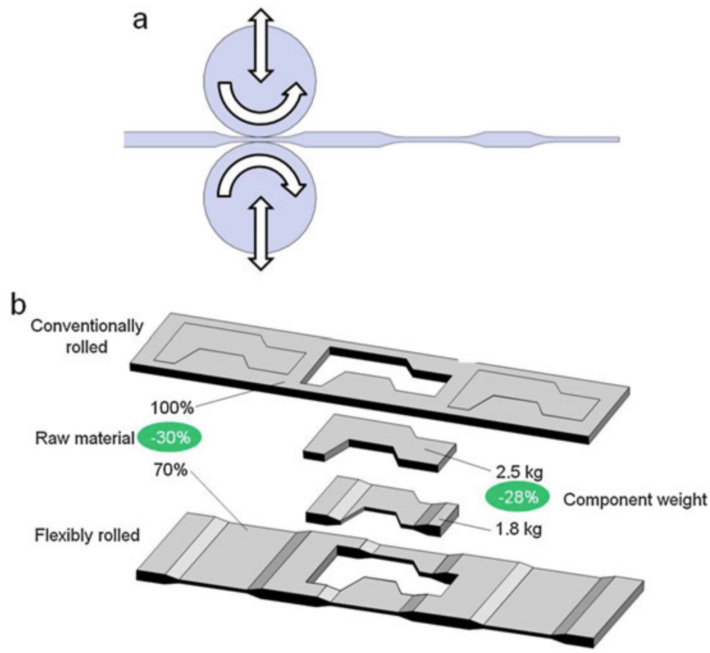
In the shear-dominated range ($l_c/h_m < 1$), the rolling force could be described by Eq. 3 according to Lugovskoi (Sandmark 1972):

$$F = 1.15 \cdot w_m \cdot l_c \cdot \sigma_y \cdot \left(1.25 \cdot \frac{l_c}{h_m} + 1.25 \cdot \ln\left(\frac{h_m}{l_c}\right)\right) \quad (3)$$

In both equations, σ_y is the flow stress, μ the friction coefficient, w_m the mean width, and h_m the mean height. The factor 1.15 is used to adopt the Tresca yield criterion to the von Mises criterion under plane-strain conditions.

Another important parameter for rolling is the torque M. A simplified method for the calculation is based on the lever arm distance of the rolling

Rolling, Fig. 6 Process principle of flexible rolling (**a**) and weight reduction compared to conventional sheet (**b**)



force resulting from the normal pressure p_x as shown in Fig. 6. The torque for a single roll is calculated as follows:

$$M = F \cdot a \quad (4)$$

where a describes the horizontal distance between the center of the roll and maximum of the normal pressure. A safe approximation for a is 0.5 times l_c. It is safe because the calculated torque is bigger than it really is Ginzburg and Ballas (2000).

Another standard question to be answered is if a rolling stock, which is brought in contact with the roll gap entry, will be drawn inside the roll gap by frictional forces. Based on a consideration of the longitudinal component of the normal force and the friction force, the following relation can be derived (von Kármán 1925). The rolling stock will be drawn into the roll gap as long as the desired thickness reduction is chosen smaller than the following relation:

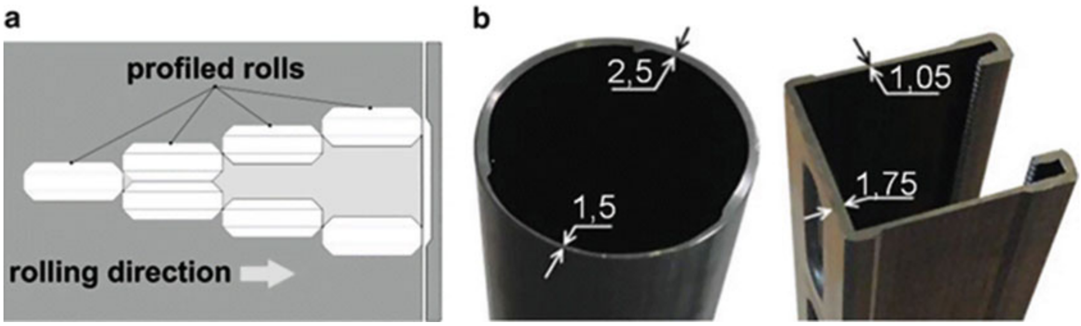
$$\Delta h \leq \mu^2 \cdot r \quad (5)$$

Further Rolling Processes

Flexible Rolling and Strip Profile Rolling

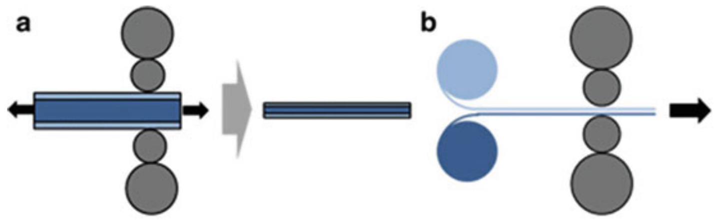
Flexible rolling can be used to create a defined thickness distribution in the rolling direction. This method is industrially established to create load-optimized parts, for example, for automotive components. The process principle and the implemented roll gap control for the flexible rolling are illustrated in Fig. 6a. Figure 6b demonstrates that the use of flexible rolled sheets may not only reduce the weight of the component itself but may also reduce the weight of production scrap compared to the sheet from conventional flat rolling.

Strip profile rolling in its objective is comparable to flexible rolling, but instead of a thickness distribution in rolling direction, a defined thickness distribution in width direction is created to produce load-optimized metal strips. To achieve this without flatness defects, material flow lateral to the rolling direction is imposed by the use of small rolls. These small profiled rolls are arranged in an alternating offset pattern as shown in Fig. 7a. Two different examples for

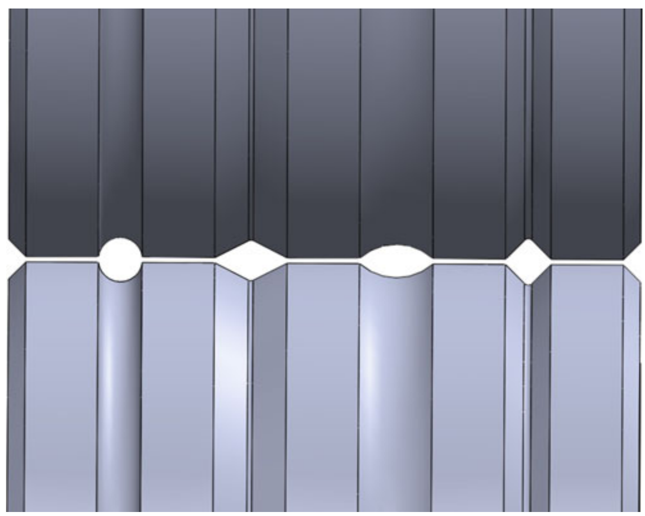


Rolling, Fig. 7 Roll arrangement for strip profile rolling (**a**) and load-optimized profiles (**b**)

Rolling, Fig. 8 Two-side reverse roll bonding of slabs (**a**) and one-side single-pass roll bonding of strips (**b**)



Rolling, Fig. 9 Sketch of caliber rolls showing standard geometries used in caliber rolling (round, diamond, oval)



load-optimized profiles made of tailor rolled strips are presented in Fig. 7b.

Roll Bonding

The main objective of roll bonding is the bond creation between different layers in combination with a flat rolling process. Thereby, it is possible to achieve tailored properties across the sheet thickness. In aeronautics, for example, bonding layers like pure aluminum (AA1050) are applied on a high-strength aluminum alloy (AA2024) for corrosion protection. Figure 8 shows two schemes of different roll bonding processes used for slabs or strips.

Caliber Rolling

Caliber rolling is used for the production of profiled long products such as rails and I-beams.

Figure 9 shows a sketch of different caliber geometries used for the production of long products. Different geometries like round, oval, and diamond are used to achieve forming sequence resulting in a homogenous forming of the material. The dimensioning of a new caliber sequence is mainly based on experience as only simple calibers can be calculated directly. Neumann presented a guideline with the most relevant aspects that should be considered calculating a new caliber sequence mainly based on the reduction of the cross section in each pass (Neumann 1975).

Cross-References

- ▶ Bonding
- ▶ Composite Materials
- ▶ Flow Stress, Flow Curve
- ▶ Roll-Forming

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Rotary Tools

▶ Self-Propelled Rotary Tool

Rotating Tool

▶ Turning with Rotary Tools

Roughness

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Synonyms

Surface roughness

Definition

Dimensional irregularity of a surface, its deviations from a mathematical flat.

Theory and Application

Importance of Roughness for the Function of a Workpiece

Functional aspects that are affected by surface roughness can be described by 1-, 2-, and 3-body interactions.

Interaction with a Single Surface

The transmission and reflection of electromagnetic waves is determined by the surface geometry (see entry "▶ Reflectivity"), especially the scattering by the surface. One can look through window glass due to the fact that the surface roughness *Ra* (<10 nm) is much smaller than the wavelength of light (yellow light: 470 nm). The difference between "gloss" and "mat" of, e.g.,

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pictures or paint is determined by the surface roughness. For the final optical properties of an object also the shape is essential.

For good adhesion of coatings to a surface, a certain roughness may be needed. A simple example is the grinding of a surface before it is painted.

Chemical reactions with a surface depend on the roughness. A reflective surface of a lapped gauge has very little corrosion under normal circumstances, even if it is made from a rapidly corroding steel.

Interaction Between Two Surfaces

We give here some aspects and properties that are affected or determined by the surface roughness:

- The coefficient of friction between two bodies
- The presence/remain in a liquid film between two bodies (lubrication)
- Sealing by means of a threaded connection or a pen/hole connection
- Stiffness of a connection
- Plastic or elastic deformation at contact between two bodies
- Thermal conductivity between two bodies
- Electrical conduction between two bodies
- Wear/fatigue contact between surfaces

Interaction Between Three Surfaces

The primary example here is the bearing, the stiffness and friction on moving, the roughness of the balls, and the surfaces between which the moving occurs.

The quantification of these aspects and determine the most relevant roughness parameter is the trickiest part of a design where the roughness is important. Because this is different for each problem there are barely general guidelines.

Roughness and Manufacturing Process

Each machining process has its capabilities and limitations when it comes to reach a certain surface structure. Surfaces produced by various machining processes will look different, even though the most widely used roughness parameter *Ra* is equal.

Roughness, Table 1 Typical roughness due to various machining processes

Process	Range of *Ra* in μm
Sandblasting	6–50
Cutting	1.6–50
Drilling	0.8–12
Spark erosion	0.8–12
Die casting	0.4–6
Milling	0.2–25
Grinding	0.02–6
Honing	0.02–1.6
Polishing	0.005–0.8
Lapping	0.005–8

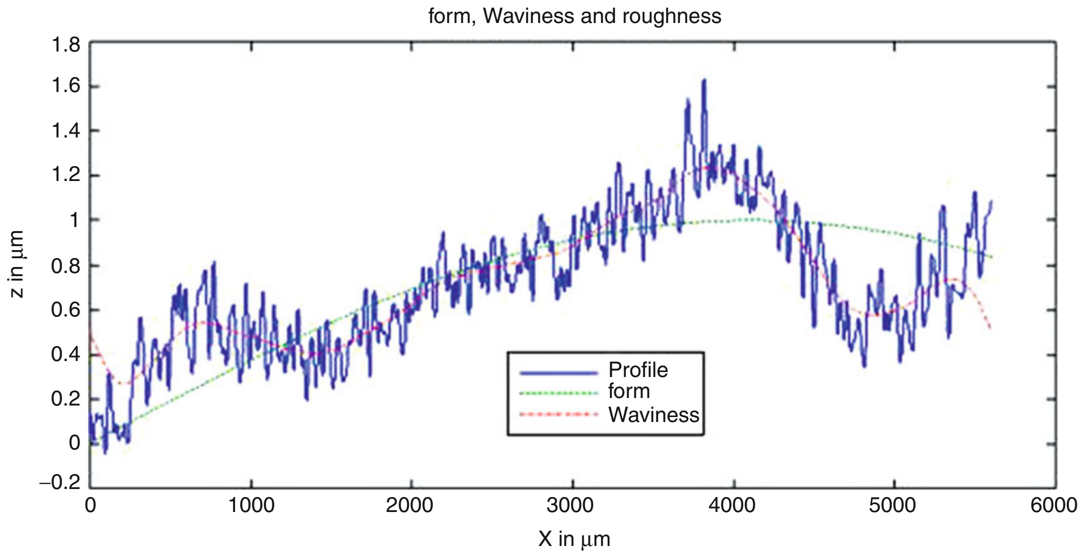
Table 1 shows what surface roughness *Ra* is normally achieved by the machining process mentioned.

In production engineering, surface roughness is that part of the irregularities on the surface left by the shaping process, which are inherent to the material removal process itself. This contrasts with the undulations mostly due to the imperfect behavior of an individual machine. In general, the roughness depends on the basic form of the tool, especially in the case of turning and grinding, but it also depends on irregularities in the ways caused by micro-cracks, material build-up on the tool and other causes. Although *Ra* is the most commonly used surface parameter, it is arguably not the most appropriate for many purposes. Many, many other surface parameters can be, and have been, defined.

Distinction Between Form Deviation, Roughness, and Waviness

In general, the deviation from the ideal shape can be distinguished in three distinct areas in which the structure of a surface is constructed, namely:

(a) Form deviation caused by the process by which the shape is applied, removing it may well not be machined. These are long-wavelength abnormalities, abnormalities which guide development.
(b) Waviness, usually caused by factors such as machine and tool deflection, vibration of machine, and machining process (chatter).



Roughness, Fig. 1 Illustration of roughness, waviness and form deviation

Waves are predominantly periodic appearing surface deviations, with a wavelength greater than the surface roughness. The relationship between wavelength and depth is between 100:1 and 1000:1.

(c) Roughness caused by the shaping tool, e.g., machining grooves and the structure inside. The relationship between wavelengths and depth can be between 150:1 and 5:1.

Practically it is difficult to draw the line between these different domains of scale, especially because waviness is usually measured as part of the form deviation (Fig. 1).

The subdivision waviness/roughness is essentially deliberate, but in practice this is fixed in standards with the most common distinction is at a wavelength of 0.8 mm. More specific guidelines for this division and the related filtering are given in ISO 4288 (1996) and ISO 16610-21 (2011), respectively.

Cross-References

▶ Bearing
▶ Drilling
▶ Grinding
▶ Honing
▶ Lapping
▶ Polishing
▶ Reflectivity
▶ Surface Parameter
▶ Wear Mechanisms

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Roughness Filtering

▶ Surface Texture Filtering

Roughness Parameter

▶ Surface Parameter

Roughness Relations

▶ Functional Correlation

Rounded Cutting Edge

▶ Cutting Edge Geometry

Roundness

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Definition

A form tolerance that prescribes the largest possible deviation of a circle from its geometrical ideal form (Pfeifer and Schmitt 2010). The roundness tolerance determines that in each section perpendicular to the axis of a toleranced cone-formed element, the actual profile, or the actual contour line, must lie between two concentric circles within the same plane, which are at the distance of the tolerance value. For sphere-formed elements, this tolerance is valid for each intersection through the center.

Theory and Application

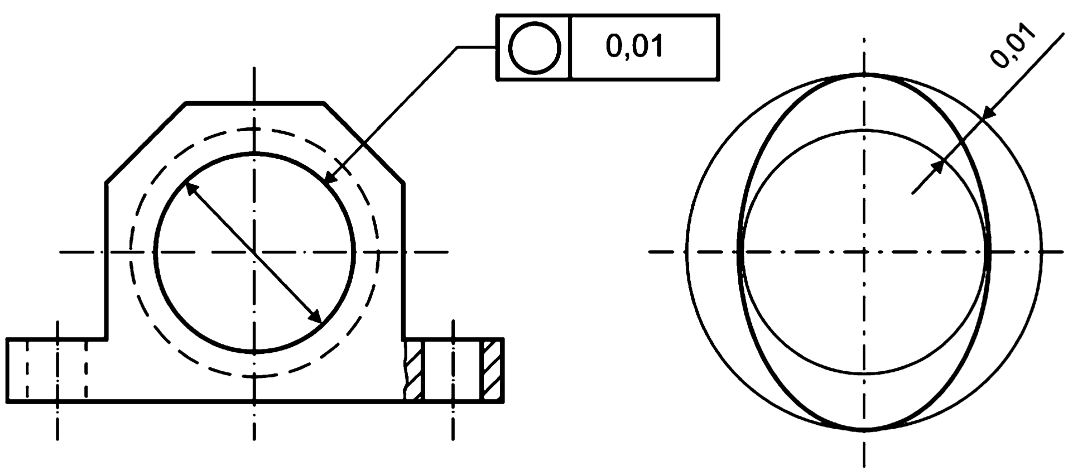
The sample workpiece has a drill hole for the bearing with a roundness tolerance of 0.01 mm (Fig. 1). Roundness tolerances can also be used for arcs of circles with less than 360° coverage (Pfeifer and Schmitt 2010).

Assessment

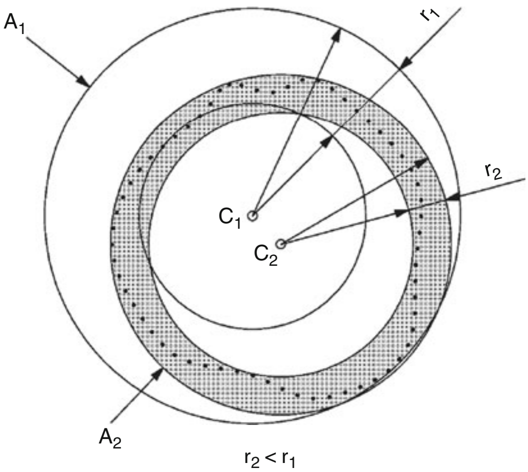
The roundness of a single toleranced feature is deemed to be correct when the feature is confined between two concentric circles such that the difference in radii is equal to or less than the value of the specified tolerance. The location of the centers of these circles and the value of their radii shall be chosen so that the difference in radii between the two concentric circles is the least possible value (DIN EN ISO 1101 2014).

An example for a particular cross section is given as follows (see Fig. 2):

Possible locations of the centers of the two concentric circles and their minimal difference in radii.
Center (C1) of A1 locates two concentric circles with difference in radii, r1.



Roundness, Fig. 1 Roundness



Roundness, Fig. 2 Roundness tolerance (DIN EN ISO 1101 2014)

Center (C2) of A2 locates two concentric circles with difference in radii, r2.
In the case of Fig. 2, r2 < r1.

Therefore the correct locations of the two concentric circles are the ones designated in A2. The difference in radii r2 should then be equal to or less than the specified tolerance.

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