A

Ability to Be Machined

► Machinability

Abrasive Grains

► Abrasive Material

Abrasive Material

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Synonyms

Abrasive grains

Definition

An abrasive grain is a hard, tough substance containing many sharp projection cutting edges or points. It is used as a cutting tool to penetrate and cut away material that is softer than itself. **Abrasive Materials** used for abrasives are generally characterized by high hardness and moderate to high fracture toughness.

Theory and Application

Abrasive materials are usually classified into two groups, natural and manufactured ones. The natural abrasives are generally referred to as those that have been produced by the uncontrolled forces of nature and because of that, they can contain many impurities and vary in quality. Emery, corundum, quartz, flint, garnet, diamond, tripoli, diatomaceous earth, sandstone, pumice, and natural sharpening stones are some of them (Krar 1995; Jacobs 1928). On the other hand, artificial abrasives were first developed in the late nineteenth century and overcame the problems of impurities and inconsistencies, since their manufacture could be carefully controlled. Some manufactured abrasives are carbide of silicon, aluminum oxide, glass, and the metallic abrasives such as steel wool and steel shot and grit (Krar 1995; Jacobs 1928) (Table 1).

Properties of Abrasives

The abrasive grain must be harder than the material being ground so that it can penetrate the surface and remove a suitable chip (Fig. 1). In addition to this, the abrasive grain must be tough enough to withstand the shock (thermal and mechanical) of grinding and yet be friable

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Abrasive Material, Table 1 List of abrasive materials

Abrasive glass	Glass has been utilized as an abrasive for a number of purposes, before the advent of manufactured abrasives. The glass was powdered very fine and used with water or oil. It is inexpensive and abundant and under certain conditions with the form of "glass paper" has been known to give good results (Jacobs 1928)
Aluminum oxide	Aluminum Oxide is an electric furnace product made by fusing materials high in alumina, such as bauxite. Is the most widely used abrasive, generally used for ferrous alloys, high tensile materials and wood.Aluminum oxide is used for making grinding wheels for finishing materials of high tensile strength. It is used in grain form for setting up polishing wheels, coating abrasive paper and cloth, and to a certain extent for finishing stone, glass, etc. The ordinary variety of aluminum oxide is used for general steel grinding on both rough and precision work, while a refined variety is used largely for grinding alloy steels, for cutter sharpening, etc. (Jacobs 1928)
Carbide of silicon	Carbide of silicon is a manufactured abrasive, a chemical composition of two elements, carbon and silica. Carbide of silicon has a well defined crystalline structure and it is exceedingly hard and sharp. It is nearly as hard as a diamond. Carbide of silicon is used for the manufacture of grinding wheels, being especially valuable for grinding cast iron and brass. It is also an economical abrasive for grinding stone, glass, etc. In grain and powder form it is used for stone finishing, glass grinding, etc. Coated on paper and cloth it is used for a diversity of purposes such as leather finishing, paint rubbing, etc. (Jacobs 1928)
Corundum	This mineral is an impure form of the ruby, a composition of alumina and oxygen, Al_2O_3, with impurities such as silica, ferric oxides, etc., and combined water. Corundum in reality is a pure form of emery as its major constituent is alumina. As an abrasive, corundum has many uses. It makes excellent grinding wheels for finishing materials of high tensile strength. It is also used for coating abrasive cloth, and to some extent in grain form for setting up polishing wheels. In the finer grades, it is considered an ideal material for grinding glass and finds many applications in the lens-making industry (Jacobs 1928)
Cubic boron nitride (CBN or Borazon)	CBN is a synthetic material, which although discovered in the early nineteenth century was not developed as a commercial material until the latter half of the twentieth century. CBN is the second hardest material next to diamond. It was first synthesized in 1957, but it is only in the last 15 years that commercial production of CBN has developed. The material is widely used both as bulk materials and as in other forms such as thin films, fibers and coatings in electronic and ceramic composite applications. Boron nitride has unique chemical and physical properties, such as low density, high melting point, high thermal conductivity, superior chemical inertness and high electrical resistivity. Its chemical inertness leads to application as thermocouple protection sheaths, crucibles and linings for reaction vessels though as above oxidation must be avoided. Cutting tools and abrasive components particularly for use with low carbon ferrous metals have been developed using CBN. In this application the tools behave in a similar manner to polycrystalline diamond tools but can be used on iron and low carbon alloys without risk of reaction. Additionally, CBN is used for substrates for mounting high density and high power electronic components where the high thermal conductivity achieved allows efficient heat dissipation. Due to its high hardness and excellent wear resistant properties, coatings of CBN have been developed (Dasa et al. 2009)
Diamonds	Diamonds are of two general types, the white or gem variety and the black or carbonado stones. Bort diamonds as used for grinding wheel truing are in reality imperfect gem stones which because of flaws, construction characteristics, etc., cannot be cut into gems (Jacobs 1928). In 1957, the commercial manufactured of diamond for sale as a consumable abrasive was made possible. Diamond is suited to grinding tungsten carbide, natural stones, granite and concrete, as well as more sophisticated ceramics and cermets. However diamond is not suited for grinding steels due to very aggressive chip formation edges (Salmon 1992)

(*continued*)

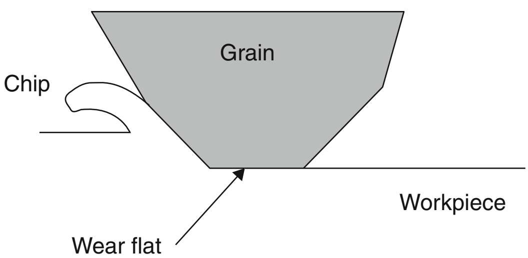
Abrasive Material, Table 1 (continued)

Diatomacous earth	Diatomaceous earth is more commonly known as infusorial earth. It sometimes is referred to by its German name, kieselguhr. Diatomaceous earth is a soft, white, porous rock composed of the siliceous skeletons of small aquatic plants called diatoms. As an abrasive, diatomaceous earth is used in the manufacture of polishing compositions, often being marketed under the name of tripoli. It is considered to be a much purer form of silica than true tripoli. It is used on buffing wheels for cutting down before final polishing. This material has many other uses aside from its application for abrasive purposes (Jacobs 1928)
Emery	Emery is a mixture of aluminum oxide and iron in the form of magnetic or hematite. Emery is used for a diversity of purposes. In the form of grinding wheels it is used for snagging heavy steel and malleable castings or for backing up manufactured abrasive wheels sold for this purpose. Emery is particularly adapted to this work as its grains hold to the bond with a tenacity that is productive of long wheel life. In the form of coated paper and cloth large quantities of emery are used in various industries. In grain and powder form emery forms an excellent polishing, large quantities being used for setting up polishing wheels for finishing practically all metals. It also is used for glass grinding (Jacobs 1928)
Emery cake	A composition made of fine emery with a suitable binder, used for treating buffing wheels for cutting down operations. It is a sharp fast cutting composition for the work in question and is used on rough castings, aluminum, sheet metal, etc. (Jacobs 1928)
Emery string	This material is stout flax cord impregnated with flour emery and a grease binder. It is used in sewing-machine factories for “stringing out” holes in thread guides and in musical instrument manufacture for removing burrs from holes in pegs and tail pieces (Jacobs 1928)
Flint	This material is a very hard mineral substance. Its main component is silica. Due to the fact that it breaks with a conchoidal fracture it lends itself admirably to fabrication by crude methods
Garnet	Garnet is a name given to a certain group of minerals possessing similar physical properties and crystals forms. The group consists of seven different species, all of which are silicates of aluminum, calcium, magnesium, iron, manganese, or chromium. Garnet is usually used for machining of wood (Jacobs 1928)
Lime	Metallic abrasives are both steel and iron, made in various forms for different abrasive purposes. They are used for various purposes such as sawing, polishing, rubbing, etc., on stone work. Finer sizes are used for sandblasting (Jacobs 1928).
Pulp stones	The large stones used for grinding wood pulp in the paper making industry are a selected variety of sandstone or artificial abrasive wheels (Jacobs 1928)
Pumice	Pumice is of volcanic origin, thus an igneous rock of an amorphous nature. It often contains impurities such as feldspar and hornblende. Pumice is used as an abrasive for a diversity of purposes. It is used in the automobile body finishing industry in the form of hone gangs for rubbing down rough stuff on automobile bodies. In powder form it is used with water for rubbing paint and varnish (Jacobs 1928).
Putty powder	Putty powder is oxidized tin, burnt with a certain amount of lead litharge. Its main advantage is that it imparts a permanent polish on cut glass, marble, granite, etc. (Jacobs 1928)
Quarts	A well known and common material composed of silicon dioxide or silica, SiO_3. Quartz is a valuable abrasive for many purposes. In grain form it is used for grinding plate glass and glued on belts it makes an excellent medium for sanding handles. It is employed for sandblasting, stone sawing, etc. It is not an efficient abrasive for grinding wheel manufacture, but it sometimes is employed in wheel mixtures in small quantities for specific reasons, such as making an open cutting wheel for knife grinding (Jacobs 1928)

(*continued*)

Abrasive Material, Table 1 (continued)

Rouge composition	A material composed of rouge mixed with a suitable binder and molded in cake form. It is used for buffing gold, silver, platinum and also for fine finishing on glass, brass, nickel steel, etc. This material was one of the first buffing compounds to be used (Jacobs 1928)
Sandstone	Sandstone is the oldest natural abrasive known. It is a sedimentary rock formed of small grains of silica or quartz firmly cemented together with silica. The material is quarried out by open-cut methods, graded and selected and formed into grindstones for various purposes. Pulpstones as used for grinding wood pulp for paper making also are a variety of sandstone and this branch of the grindstone business is probably the most important today, due to the fact that natural sandstones are being replaced gradually by abrasive wheels (Jacobs 1928)
Sharpening stones	Sharpening stone is a general name given to any stone natural or artificial to be used by hand. Manufactured abrasive stones are made by the same methods employed in grinding wheel production. The finished stones as they come from the vitrifying kilns are rubbed on circular cast iron revolving beds to smooth their surfaces (Jacobs 1928)
Steel wool	The product, which merely consists of long steel shavings or fibers, finds wide application as an abrasive or polishing medium as a substitute for emery cloth, sand paper or pumice stone for cleaning hollow ware, rheostats, patterns, tools, windows, brass sign plates, railings, machine parts, enameled ware, cooking utensils, bathroom fixtures, mirrors, cut glass and for removing paint from marble, tile, glass and porcelain. Large quantities also are consumed by shipbuilding companies, furniture and woodworking factories and in the household. In japanning work any drips, runs or other defects are smoothed out by steel wool with the result that after the second dip no scratches are visible (Jacobs 1928)



Abrasive Material, Fig. 1 Grain penetrating ground surface

enough to fracture and produce new cutting edges (Krar 1995; Salmon 1992). In general an abrasive should possess four properties in order to cut efficiently:

- **Hardness**: The ability of a material to scratch or penetrate another material. This is measured with Knoop scale (Krar 1995; Salmon 1992).
- **Heat Resistance**: The ability of the abrasive grain to withstand the heat of grinding without becoming dull (Krar 1995).
- **Toughness**: The ability of the abrasive grain to resist impact and pressures created during the grinding operation (Krar 1995).
- **Friability**: The ability to fracture under stress along certain cleavage lines so that as the cutting edges become dull, part of the grain brakes off and presents new cutting edges (Krar 1995).

Abrasive Processes

Abrasive machining processes are machining processes where material is removed from a workpiece using a multitude of small abrasive particles. These manufacturing techniques employ very hard granual particles in machining, abrading, or polishing to modify the shape and surface texture of the manufactured parts. Abrasive processes are mostly used to produce high quality parts to high accuracy and to close tolerances. In addition to this, these processes are the natural choice of machining and finishing hard materials and hardened surfaces. Most abrasive processes can be categorized into one of the following four general groups (Marinescu et al. 2004):

Grinding

Grinding is a finishing process used to improve surface finish, abrade hard materials, and tighten the tolerance on flat and cylindrical surfaces by removing a small amount of material. Grinding is one of the main methods of precision manufacturing and the process quality depends to a large extent on the experience of the operator (Durgumahanti et al. 2010). Grinding, in general, is a very complex material removal operation involving cutting as well as plowing and rubbing between the abrasive grains and the work material (Shaw 1972, 1996). In grinding, the abrasive tool is a grinding wheel that moves at a high surface speed (conventional: 20–45 m/s, High speed: 140 m/s) compared to other machining processes such as milling and turning. Grinding takes place with and without lubrication, but the "wet" grinding is preferred, where is possible, due to the reduced frictional losses and improved quality of the surfaces produced (Marinescu et al. 2004).

Shaw (1996) classified the grinding process into two categories, namely, form and finish grinding (FFG) and stock removal grinding (SRG). The primary objective in FFG is to obtain the required form, finish, and accuracy while the primary objective in SRG is to obtain high removal rate. In FFG, fine grain size conventional abrasives (e.g., alumina, SiC) in a vitrified bonded grinding wheel are generally used. The wheels are periodically dressed, conditioned, and trued to maintain sharp cutting edges, to remove metal build-up on the grains or loading of the wheel (metallic chips occupying in the void space between the grains), and to maintain roundness of the wheel. In SRG, coarse grain size abrasives, such as regular alumina, alumina-zirconia are used in a resin bonded grinding wheel. Sometimes, the cut-off wheels are reinforced with fiberglass to prevent catastrophic failure during use. Cut-off and snagging operations come under the category of SRG. Abrasive cut-off is used for parting materials and snagging is used for cleaning of the castings (namely, removal of gates, runners, risers from castings). The wheels used in the cut-off operation are consumed without ever being dressed (Hou and Komanduri 2003).

Honing

Honing is an abrasive machining process that produces a precision surface on a metal workpiece by scrubbing an abrasive stone (grain) against it along a controlled path. Typically is used to achieve a finishing surface in the bore of a cylinder. Honing is primarily used to improve the geometric form of a surface, but may also improve the surface texture (Marinescu et al. 2004).

In honing, the abrasive particles are fixed in a bonded tool like grinding. The tool moves at a low speed relatively to the workpiece (0.2–2 m/s). Combined rotation and oscillination movements of the tool are designed to average out the removal of material over the surface of the workpiece and produce a characteristic "cross-hatch" pattern favored for oil retention in engine cylinder bores. In addition to this, a honing tool is flexibly aligned to the surface of the workpiece meaning that eccentricity of the bore relative to an outside diameter cannot be corrected (Marinescu et al. 2004).

Lapping

Lapping is an abrasive machining operation, in which two surfaces are rubbed together with an abrasive between them. To be more specific, during a rough chemical-mechanical-polishing (CMP) process, a sample (such as a metal, ceramic, plastic, glass, or silicon substrate) is machined, smoothed, and planarized to a high degree of refinement or accuracy using a rotating, serrated, cast-iron-alloy circular plate and an abrasive slurry grit in water suspension applied to the plate in a controlled fashion. Typically, a soft material – called a lap – is charged with an abrasive. The lap is then used to cut a harder material – the workpiece. The abrasive embeds within the softer material which then acts as a holder for the abrasive and permits it to score across and cut the harder material. To maintain the required geometry of the lap and the workpiece surface, it is necessary to be paid careful attention to the nature of the motions involved to average out the wear across the surface of the lap (Marinescu et al. 2004).

Lapping can be used to obtain a specific surface roughness; it is also used to obtain very accurate surfaces, usually very flat surfaces. A typical range of surface roughness that can be obtained without resort to special equipment would fall in the range of 1–30 Ra.

High-speed lapping, also known as fine grinding or flat honing, uses a fixed abrasive wheel in place of the wet slurry. This dramatically reduces the lengthy cleaning process and eliminates grit impregnation. Advanced machine controls combine the rapid stock removal rate of traditional grinding with the precision finishing of traditional flat lapping. Automated systems to load and unload part further speed up the process. High-speed lapping can finish parts up to 20 times faster than traditional flat lapping. This yields significant cost savings, often up to 40 % versus traditional lapping. In fact, high-speed lapping can even cost less than traditionally low-cost grinding methods, since simple inexpensive parts carriers replace costly fixtures. High-speed lapping is ideal for all types of metals, including steel, brass, aluminum, phosphorus bronze, tungsten carbide, cast iron, and powder metals. The process is also used for plastic, ceramic, glass, carbon, and other materials.

Polishing

Polishing, like lapping, also employs free abrasive. In this case, pressure is applied on the abrasive through a conformable pad or soft cloth. This allows the abrasive to follow the contours of the workpiece surface and limits the penetrations of individual grain into the surface. Polishing with affine abrasive is a very gentle abrasive action between the grain and the workpiece, thus ensuring a very small scratch depth. The main purpose of polish is to modify the surface texture rather than the shape and remove material in a very slow rate (Marinescu et al. 2004).

Cross-References

- ▶ Grinding
- ▶ Grinding Wheel
- ▶ Honing
- ▶ Lapping
- ▶ Polishing

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Abrasive Water Jet

▶ Water-Jet Cutting

Accuracy

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Synonyms

Accuracy of measurement; Measurement accuracy

Definition

Closeness of agreement between a measured quantity value and a true quantity value of a measurand

NOTE 1 The concept "measurement accuracy" is not a quantity and is not given a numerical quantity value. A measurement is said to be more accurate when it offers a smaller measurement error.

NOTE 2 The term "measurement accuracy" should not be used for measurement trueness, and the term measurement precision should not be used for "measurement accuracy," which, however, is related to both these concepts.

NOTE 3 "Measurement accuracy" is sometimes understood as closeness of agreement between measured quantity values that are being attributed to the measurand.

(ISO/IEC Guide 99 2007, Definition 2.13)

Theory and Application

Let us start with the definition of accuracy as given in (ISO/IEC Guide 99 2007), the International Vocabulary of Metrology (VIM), see "Definition."

From this definition we have to conclude that the term "accuracy" should be used just for general comparison, that is, a measurement or a measuring instrument is more accurate than another. An example: a roundness measurement carried out on a roundness measurement machine (or roundness tester) is generally more accurate than a roundness measurement carried out on a three-axis coordinate measuring machine (CMM); if we use a high precision CMM, apply a precision rotary table on the CMM and apply a special probe system; then the measurement with the CMM and the roundness measuring machine might be of the same accuracy.

Nevertheless, we may define accuracy classes, also according to the VIM (ISO/IEC Guide 99 2007, Definition 4.25).

Accuracy Class

Class of measuring instruments or measuring systems that meets stated metrological requirements that are intended to keep measurement errors or instrumental uncertainties within specified limits under specified operating conditions

NOTE 1 An accuracy class is usually denoted by a number or symbol adopted by convention.

NOTE 2 Accuracy applies to material measures. Material measure (ISO/IEC Guide 99 2007, Definition 3.6): measuring instrument reproducing or supplying, in a permanent manner during its use, quantities of one or more given kinds, each with an assigned quantity value, for example, line scale and gauge block. And for gauge blocks, we know different accuracy classes.

According to Note 2 of the definition, the term "accuracy" is sometimes mixed up with "measurement trueness" and "measurement precision." Therefore, we have a look at these two terms that are defined in ISO/IEC Guide 99 (2007), definitions 2.14 and 2.15.

Measurement Trueness (or Trueness of Measurement or Trueness)

Closeness of agreement between the average of an infinite number of replicate measured quantity values and a reference quantity value

Note 1 Measurement trueness is not a quantity and thus cannot be expressed numerically, but measures for closeness of agreement are given in ISO 5725 (1994–2005).

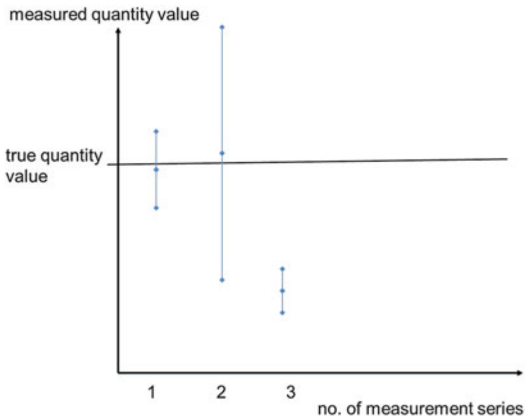
Note 2 Measurement trueness is inversely related to systematic measurement error, but is not related to random measurement error.

Note 3 Measurement accuracy should not be used for "measurement trueness" and vice versa.

Measurement Precision (or Precision)

Closeness of agreement between indications or measured quantity values obtained by replicate measurements on the same or similar object under specified conditions

NOTE 1 Measurement precision is usually expressed numerically by measures of



Accuracy, Fig. 1 Different measurement series represented by mean value and plus/minus standard deviation. Best measurement accuracy, measurement series 1; best measurement trueness, measurement series 1 and 2; and best measurement precision, measurement series 3

imprecision, such as standard deviation, variance, or coefficient of variance under the specified conditions of measurement.

NOTE 2 The "specified conditions" can be, for example, repeatability conditions of measurement, intermediate precision conditions of measurement, or reproducibility conditions of measurement (see ISO 5725–2 1994).

NOTE 3 Measurement precision is used to define measurement repeatability, intermediate measurement precision, and measurement reproducibility.

NOTE 4 Sometimes "measurement precision" is erroneously used to mean measurement accuracy.

Figure 1 shall help to explain the definitions of "accuracy," "measurement trueness," and "measurement precision." Figure 1 shows the result of three measurement series that each consists of a large number of single measurements. Each series is represented by its mean value and plus/minus the standard deviation. Each measurement series may have been carried out under different conditions, such as different measurement equipments, different operators, and different environmental conditions:

– Measurement series 1 shows the best accuracy and measurement series 3 the worst. Measurement series 1, represented by its mean value plus/minus the standard deviation, is closest to the true quantity value.
– Measurement series 1 and 2 show similar measurement trueness and measurement series 3 a worse measurement trueness. The averages, or the mean values, of measurement series 1 and 2 are closest to the true quantity value, much closer than the mean value of measurement series 3.
– Measurement series 3 shows the best measurement precision and measurement series 2 the worst. The standard deviation of measurement series 3 is the smallest of all three measurement series.

ISO 5725 (1994–2005) series deals with accuracy as a combination of trueness and precision, stated by systematic measurement error and random measurement error.

In the simple case of a gauge block, three major parameters define the accuracy class of a gauge block: maximum permissible flatness error, maximum deviation from nominal length, and maximum permissible length error.

For a CMM standards like ISO 10360 (2000–2011), define some parameters that could be used for defining accuracy as a combination of systematic and random errors, like the "error of indication of a CMM for size measurement, E," and the "probing error, P." However, with these parameters only a very small application range of a CMM is covered: the measurement of the distance between two nominally parallel planes approached from opposite directions and the measurement of a precision sphere. With these parameters we hardly can make a statement on accuracy of measurement of, for example, parallelism of bores and of squareness between planes.

For a complex measuring instrument, like a CMM, the definition of accuracy classes needs a large set of well-defined parameters. Many of those parameters still need to be defined.

Often we also want to apply "accuracy" to machine tools, to processes, and to manufacturing systems. For a machine tool ISO 230–2 (2006) defines accuracy of positioning of an axis. It is the result of a well-defined procedure (with selected target points, moving 5 times upwards and downwards, calculating mean positioning errors and standard deviation values in each target point, combining those to the maximum range of mean positioning errors plus repeatability, defined as 4 times standard deviation values). In the sense of the VIM definition of accuracy, this parameter would be better named “positioning performance.”

However, this accuracy of positioning describes only a very small part of the accuracy of a machine tool. For establishing accuracy classes of machine tools, we had to consider parameters on geometric errors (positioning, straightness, roll, pitch, yaw, squareness), contouring errors (based on straightness error on straight lines in space, circular error, etc.), stiffness of the machine tool, dynamic errors, and thermally induced errors.

Cross-References

▶ Error
▶ Form Error
▶ Measurement Uncertainty
▶ Precision

References

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Accuracy of Measurement

▶ Accuracy

Activity

▶ Process

Actuator

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Synonyms

Adaptronics; Smart materials; Smart structure; Unconventional actuator

Definition

Unconventional Actuator Systems

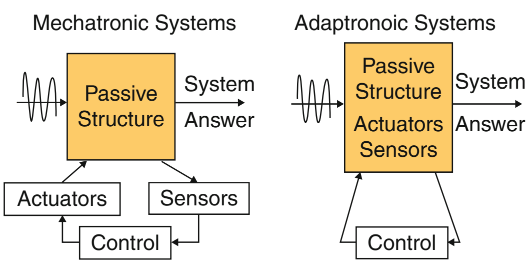
“An actuator is a functional element which connects the information processing part of an electronic control system in a technical of nontechnical process. Actuators can be used to control the flow of energy, mass or volume. The output quantity of an actuator is energy or power, often in the form of a mechanical working potential (force times displacement). The actuator control is always achieved using very low electrical power, ideally without any power consumption” (Janocha 2004).

Actuators can be classified as conventional and unconventional actuators. Conventional actuators are commonly used as essential components for mechatronic systems (see Fig. 1 (left)). These are, for instance, electrical motors, pneumatic actuators, hydraulic pistons, or relays.

Unconventional actuators are rather high integrated. They are not just an integral part of the system, they are a part of the structure itself combining sensing, actuation, and mechanical functions (see Fig. 1 (right)). Unconventional actuators are made of transducer materials. Piezoelectric actuators, shape memory alloy actuators, thermal bimorphs, and electroactive polymers are just a few examples of them.

The application of actuators made from transducer materials in highly integrated mechatronic components, such as precision positioning systems, is technically more advanced and already employed in industrial applications. Assumed such components use integrated sensors for autonomous improvement of higher-level mechanical or mechatronic structures, then they are defined as adaptronic systems in the vocabulary of mechanical engineering (see Fig. 1 (right)). Appropriate transducer materials include piezoceramics, shape memory alloys, or electromagnetically activated fluids and polymers (Neugebauer et al. 2007). Figure 2 shows the stress-strain behavior of certain transducer materials, followed by Fig. 3 which demonstrates their properties considering energy density and frequency.

It is obvious that certain actuating properties of transducer materials are far beyond the ones of conventional actuating principles. This enables to use them in special application areas such as lightweight construction, active vibration control, or the development of highly dynamic systems for instance.



Actuator, Fig. 1 Characteristics of mechatronic and adaptronic systems

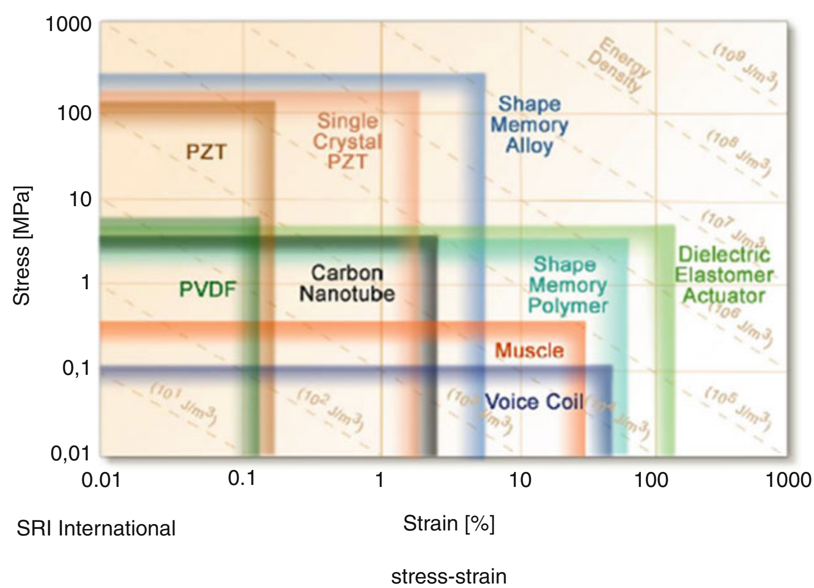
Theory and Application

Piezoceramics

Actuating Principle

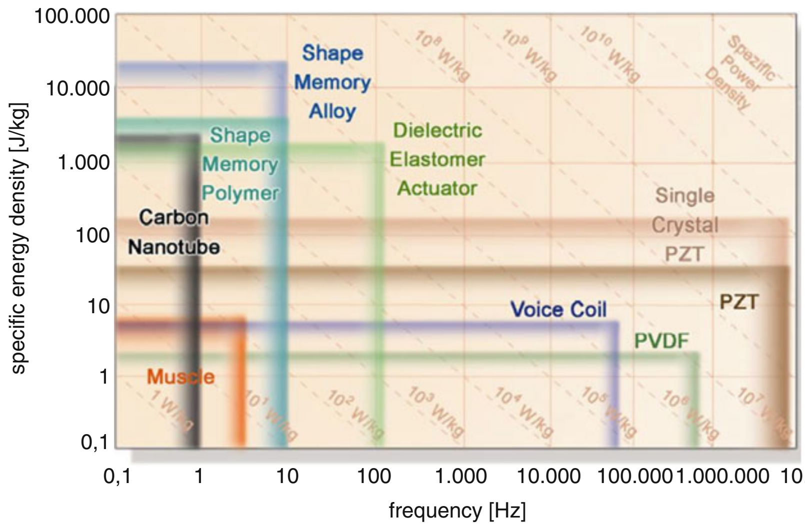
The piezoelectric effect (Fig. 4) was discovered by Pierre and Jacques Curie in 1880. The direct piezoelectric effect consists of the ability of crystalline materials (ceramics) to generate an electrical charge in proportion to an externally applied force. The direct effect is used in force transducers. According to the inverse piezoelectric effect, an electric field parallel to the direction of polarization induces an expansion of the ceramic (Preumont 1997).

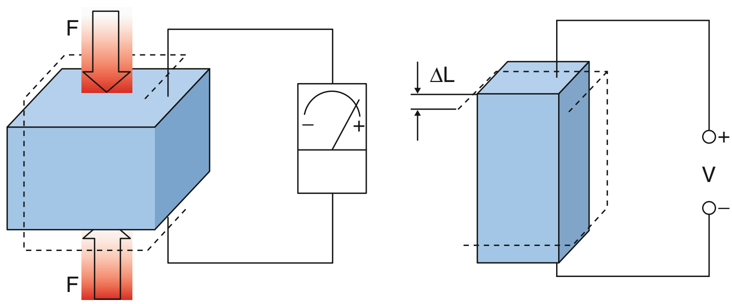
As very high electric fields correspond to the tiniest changes in the width of the crystal, this width can be changed with better-than-µm



Actuator, Fig. 2 Stress-strain behavior of transducer materials (DARPA and SRI International)

Actuator, Fig. 3 Energy density-frequency behavior of transducer materials (DARPA and SRI International)





Actuator, Fig. 4 Piezoelectric effect

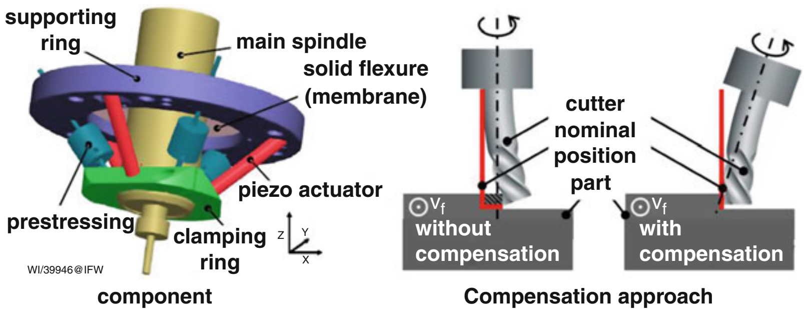
precision, making piezo crystals the most important tool for positioning objects with extreme accuracy – thus their use in ▶ actuators. Multilayer ceramics, consisting of layers thinner than 100 μm, allow reaching high electric fields with voltages lower than 150 V. These ceramics are used in two kinds of actuators: direct piezo actuators and amplified piezoelectric actuators. While a direct actuator stroke is generally lower than 100 μm (0.1 % strain), amplified piezo actuators can reach millimeter strokes.

Applications

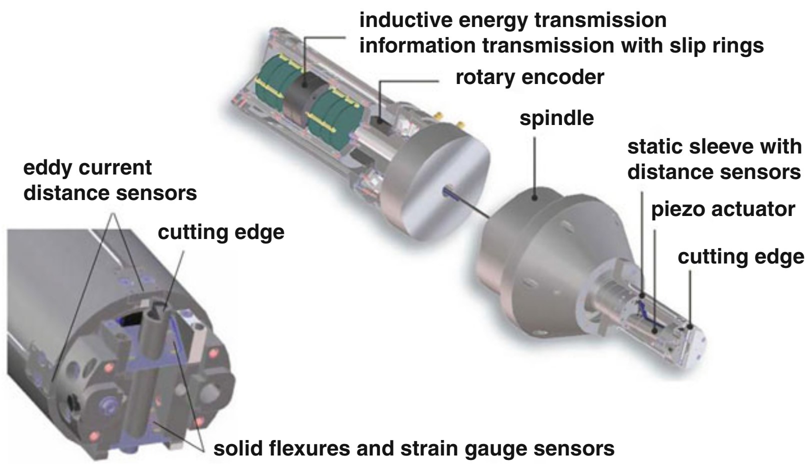
Fine Positioning

In machines which cannot execute all the correctional movements due to the absence of NC axes, the integration of additional actuators is advantageous. A solution of this kind is presented in Denkena et al. (2006) (see also "Vibration Reduction" below). Piezo actuators facilitate dynamic positioning of the tool-main spindle system in the micrometer range by a tilting motion around the X- and Y-axes and by movement in the Z-axis (Fig. 5). Movements of around ±130 μm can be generated.

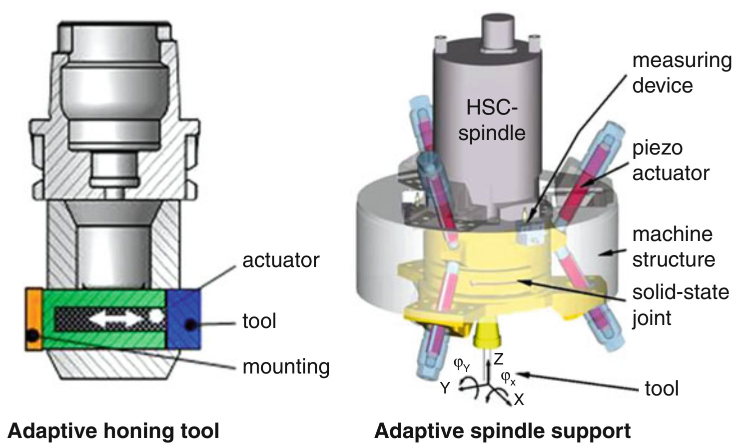
All these principles are however scarcely suited to compensation for the deflection of thin boring bars. In this area, mechatronic initiatives with additional actuators have great potential. In the solutions already known (Bushuev 1991; Katsuki et al. 1992; Koren et al. 1999; Brecher et al. 2005), the tool cutting edges can be adjusted to compensate for deflections of the boring bar. The active boring tool shown in Fig. 6 consists of



Actuator, Fig. 5 Compensation of deflection of the milling head by a mechatronic unit (Denkena et al. 2006)



Actuator, Fig. 6 Active boring bar to compensate for the deflection of the cutting edges boring processes (Brecher et al. 2005)



Actuator, Fig. 7 Adaptive tools for microstructuring and contouring (Neugebauer et al. 2010a)

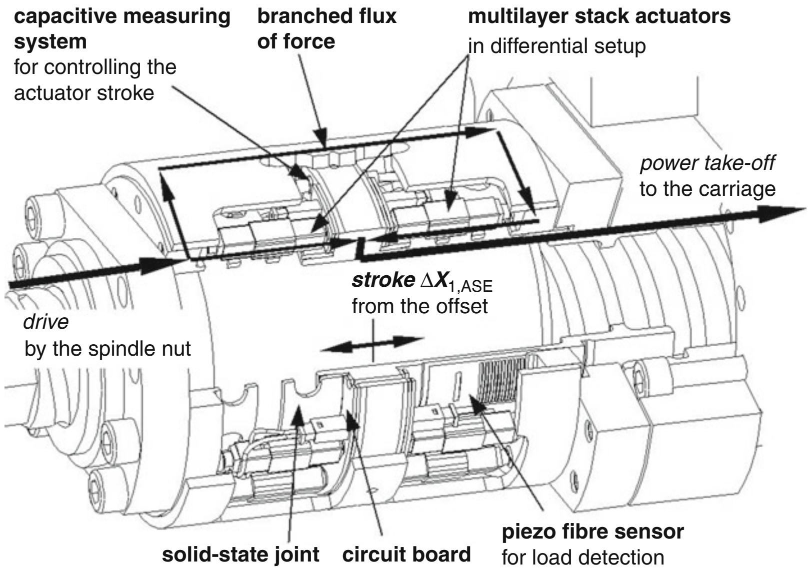
a rotating boring shaft and a vertical measuring sleeve (Brecher et al. 2005).

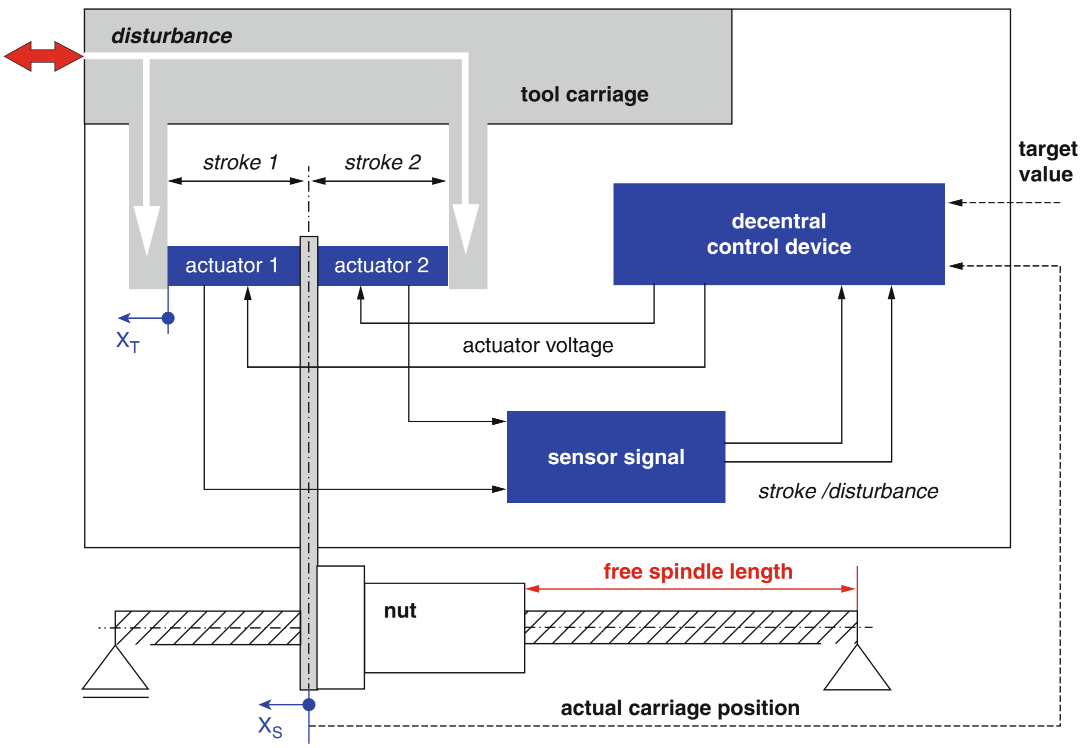
There are other approaches (see Fig. 7) which aim not just the compensation of deflections but also realize a fine positioning movement of the tool cutting edge to realize microstructuring and contouring and even noncircular boring (Brecher et al. 2005; Neugebauer et al. 2010a).

Vibration Reduction

Beyond fine positioning of tools and work pieces, piezo-based components also serve as devices for

Actuator, Fig. 8 Design concept of the actuator sensor unit (Neugebauer et al. 2010b)

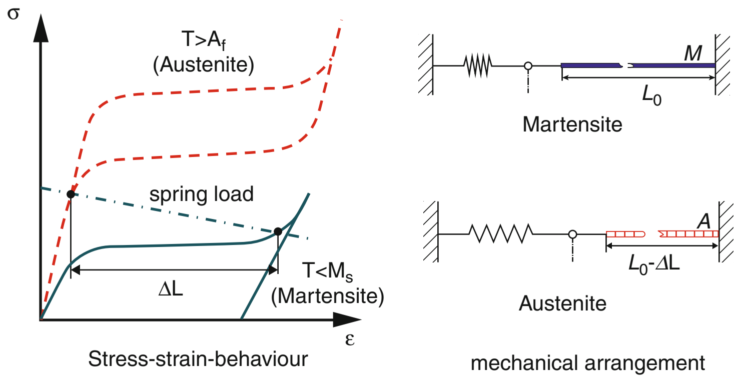




Actuator, Fig. 9 Scheme of the ASU as part of a feed axis (Neugebauer et al. 2011)

vibration reduction to enhance accuracy or to improve the dynamic behavior of drives.

Figure 8 shows a piezo-based actuator sensor unit (ASU) which is able to reduce uniaxial vibrations in ball screw driven feed axis of machine tools. The component is implemented into a feed axis and placed between the ball screw nut and the tool as seen in Fig. 9. Using this component yielded



Actuator, Fig. 10 SMA actuating principle wire against spring

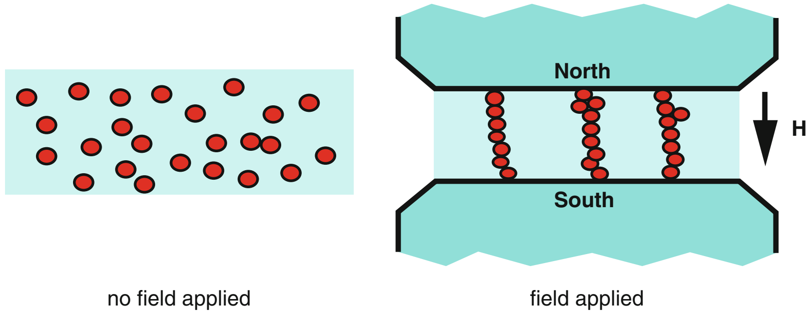
in an increase of the drives controller parameters by more than 100 % (Neugebauer et al. 2010b).

Shape Memory Alloys (SMA)

Thermal shape memory alloys are materials which offer the special ability to "remember" and reassume their original shape following permanent plastic distortion below a specific critical temperature by means of heating up above this temperature. A reversible austenite-martensite phase transformation is required for the development of the shape memory effect. Analogous to steel the high temperature phase "b" of the material is also described as austenite and low-temperature phase "a" as martensite. In an ideal situation, the austenite "b" phase is converted into the martensite "a" phase as a result of shear. Due to diffusion-free rearrangement processes in relation to the atoms, this generates a change in the stacking sequence of the crystal lattice levels and therefore a change in the structure of the crystal lattice. Consequently, two different stress-strain curves exist as shown in Fig. 10 (left). In the low-temperature phase, a small Hook region is followed by a so-called plateau stress. There the actuator (e.g., wire) can be easily deflected almost without increasing the applied external stress. After setting the stress to zero, a plastic deflection remains to the actuator. Heating the material causes the described phase transformation and results in a completely different stress-strain behavior. The Hook region is significantly wider; the Young's modulus is two to three times higher. Applying a high amount of stress causes a so-called super-elastic behavior. During the phase transformation from martensite to austenite (heating), the wire is able to perform mechanical work; see Fig. 8 (left). The amount of work depends on the mechanical boundary conditions of the actuator. In case of a free actuator, the amount of work would be zero, but the deflection would be maximum. In contrast, blocking the actuator causes a very high force but no deflection. The work output is also zero. Using a spring with a defined stiffness as boundary element instead, causes a deflection as well as a reaction force and therefore a usable workload. The amount of that workload depends on the stress-strain curves of the material and the design of the spring (see Fig. 10 (left)) (Neugebauer et al. 2011).

One of the advantages to using shape memory alloys is the high level of recoverable plastic strain that can be induced. The maximum recoverable strain these materials can hold without permanent damage is up to 8 % for some alloys (compared with a maximum strain 0.5 % for conventional steels). The yield strength of shape memory alloys is lower than that of conventional steel, but some compositions have a higher yield strength than plastic or aluminum. The yield stress for NiTi can reach up to 500 MPa.

Actuator, Fig. 11 Magento-electrorheological effect



Actuator, Table 1 Comparison between MRF and ERF (Yang 2001)

	MRF	ERF
Activating field	Magnetic	Electric
Maximum shear stress	50–100 kPa	2–5 kPa
Maximum field density	250 kA/m	4 kV/mm
Viscosity	0.1–10 Pas	0.1–10 Pas
Density	3–4 g/cm^3	1–2 g/cm^3
Maximum energy density	0.1 J/cm^3	0.001 J/cm^3

Rheological Fluids

Rheological fluids are generally a dispersion composed of a base fluid (usually a type of oil) and particles. These particles can be either polymer in electrorheological fluids (ERF) or iron based in magnetorheological fluids (MRF). If a field is applied, the so-called particle chains are built and the fluid changes its viscosity to the point of becoming a viscoelastic solid (see Fig. 11).

That causes a blockage in the flow cross section and thus increases the fluid flow resistance. Hence, the fluid is able to transmit forces. The yield stress and the transmittable forces can be controlled very accurately by varying the field intensity. Rheological fluids are thus considered valuable for manipulating viscosity over a wide range without consuming or degenerating the substance. Table 1 shows a comparison of the properties of magnetorheological and electrorheological fluids.

Due to a high magnetic energy density, MRF can apply very high shear stresses and consequently transmit high forces. ERF are thereby rather limited by the maximum applicable electric field. To achieve the same performance, more ERF has to be exposed to an electrical field. Hence, MRF-based systems can be realized with much less cross section than ERF systems although the energy consumption of both systems is almost the same. A further advantage of MRF is their activation by magnetic fields as these can be generated by common low-voltage sources. ERF rather requires high-voltage activation fields and thus necessitates complex amplifier systems. Beyond that, MRF is comparatively insensitive to contaminations, whereas ERF is very sensitive since contaminations decrease the electric strength.

However, there are some disadvantages of MRF. The high-density difference of the basis fluid and the iron particles can particularly in rotating systems cause a segregation of fluid and particles. Thus, MRF-based systems require designs where the fluid is permanently mixed. Due to high magnetic activation fields and hence the required inductance of the activation coils, the realizable working frequency of MRF is comparatively small.

Conclusion

Beyond the ongoing research on the previously described smart materials, there are a few new innovative materials. Whether they are already investigated basically, recent material-related publications show an outstanding potential for them to serve as actuator materials in the future.

A first group of new smart materials are magnetic shape memory alloys (MSM). They are a subcategory of shape memory alloys which show the thermal memory effect, as described in the previous section, as well as a magnetic memory effect. The special property of MSM materials which generates this effect is the ferromagnetic characteristic of the martensitic phase. Hence, reversible deformations of up to 10 % can be realized by applying a magnetic field. Depending on the microstructure of the material and the achieved strain, a magnetic field of about one tesla is required (Tellinin et al. 2002). The recreation of this reversible strain can be realized in two ways: thermally by heating up the material into the austenitic state and magnetically. For the magnetic recreation, a field, perpendicular to the field that caused the deformation, has to be applied. Hence, it is unimportant whether the deformation was stress or magnetic field induced. That permits a wide field of applications using the thermal or the magnetic memory effect or even combinations of both in one component. The magnetic activation, for example, possesses a contactless realization of actuator movements. Compared to conventional shape memory alloys which have to be activated thermally, MSM rather show a much higher dynamic performance because the response time of the material only depends on the setup time of the magnetic field. Currently magnetic shape memory alloys are already investigated basically. However, recent publications present the first developments of actuator concepts (Holz and Janocha 2010).

Another emerging group of smart materials is dielectric elastomer actuators (DEA). They are basically stacked compliant capacitors. Their dielectric medium consists of incompressible but deformable elastomeric material. The applied electrodes have to be designed to withstand the deformations of the polymer. When an electric field is applied to the electrodes, these capacitors react as conventional ones. Positive and negative charges appear on either corresponding electrodes. Hence, the Coulomb forces rise between the opposite charges generating mechanical pressure which forces the electrodes to move closer squeezing the elastomer. Consequently, the elastomer elongates vertically to the electric field. Usually achievable strains of DEAs are from 10% to 30%; maximum values can reach up to 300 %.

Cross-References

- ▶ Adaptive Control
- ▶ Control
- ▶ Dynamics
- ▶ Mechatronics
- ▶ Sensor (Machines)
- ▶ Vibration

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Adaptable Manufacturing/ Production

► Changeable Manufacturing

Adaptable Production System

► Flexible Manufacturing System

Adaptive Control

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Synonyms

CNC; Parameter adaptive

Definition

Adaptive Control (AC) means that the digital controller adapts itself to the time varying of parameters of the plant dynamics at each control interval. The plant is considered to be machining, grinding, and metal forming processes in manufacturing engineering. Usually the AC is designed to constrain cutting, grinding or forming forces, torque or tool deflections at a desired level by manipulating feed or speed.

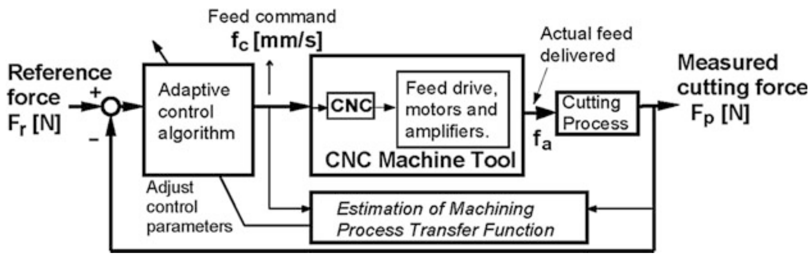
Theory and Application

Introduction

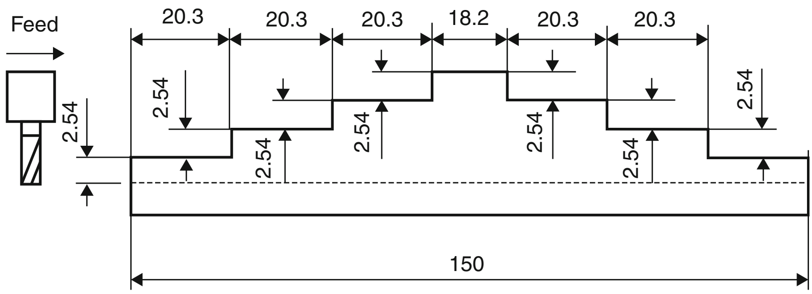
If we consider machining as an example, the cutting forces vary as the tool-workpiece engagements change due to varying part features along the tool path. If a constant, conservative feed rate is set in the NC program by considering the worst engagement conditions that lead to highest force, machining cycle time becomes unnecessarily long in the remaining tool path segments. If a high feed rate is selected, the forces may be too large, which leads to tool breakage or excessive tool deflections. AC system measures the actual cutting forces acting on the tool, identifies the time varying parameters of the combined machine tool feed drive and vibration-free cutting process dynamics (i.e., the plant), and adjusts the plant dynamic-dependent control law parameters at fixed time intervals in real time during machining.

Adaptive Control System

Block diagram of an AC system that maintains the resultant cutting forces (F_p) at a desired level (F_r) is shown in Fig. 1. The input to the AC system is the desired peak resultant force (F_r). The AC system tries to maintain the actual peak force on the tool (F_p) equal to the desired peak force (F_r). The plant consists of Computer Numerical Control (CNC) system which reshapes the command feed (f_c) indicated in the NC program using acceleration and jerk-dependent trajectory generator (Altintas et al. 2011). The feed generated by the CNC is



Adaptive Control, Fig. 1 Block diagram of an adaptive cutting force control system (Altintas 2012)



Adaptive Control, Fig. 2 Slot milling conditions to test AC algorithm (Altintas 2012)

further varied by the feed drive control law and axis dynamics, and an actual feed (f_a) is delivered to the process. The actual feed determines the maximum chip thickness which is usually linearly proportional to the maximum cutting force acting on the tool. Since the feed drive's control bandwidth is typically within 30–50 Hz, the adaptive controller can function only if the process is vibration-free and stable.

The transfer function between the actual feed and the peak resultant cutting force is usually modeled as a first-order lag in a stable cutting process. The peak force is detected usually at one spindle period in order to avoid run-out effects in multipoint cutting operations such as drilling and milling. The overall discrete transfer function between the feed command (f_c) and peak force (F_p) is considered to represent the combined dynamics of CNC, feed drives, and cutting process, and may be represented as follows:

$$G_p(z) = \frac{b_0 z + b_1}{z^2 + a_1 z + a_0} \qquad (1)$$

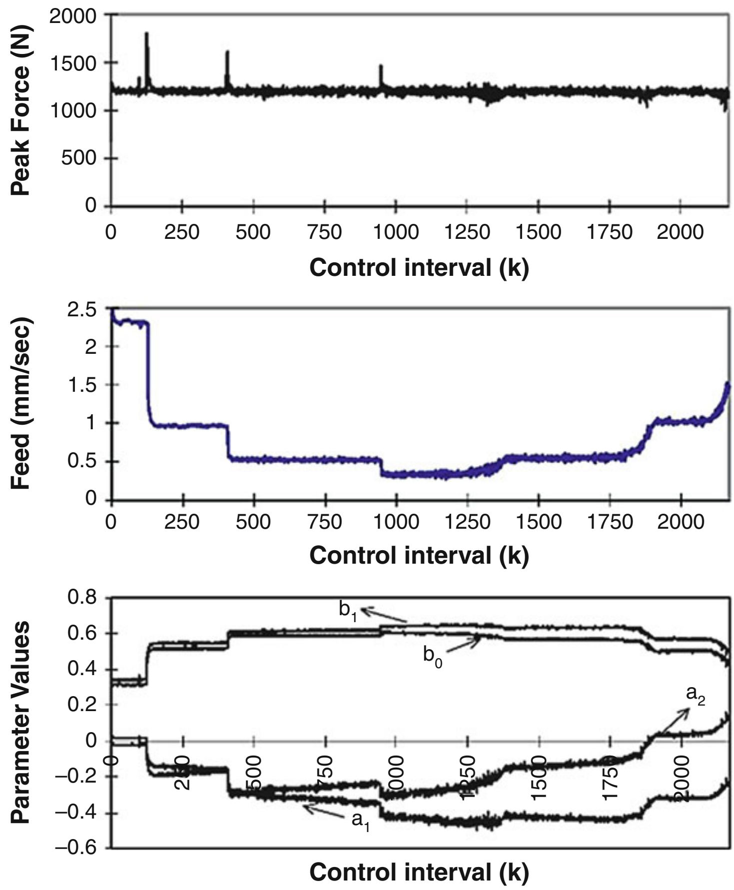
where parameters (a_0,a_1,b_0,b_1) change at each spindle period (T) as a function of axial and radial depth of cut, feed rate, number of teeth on the cutter, and cutting force coefficient. The time varying parameters are identified with recursive least squares algorithm by using input (feed – f_c) and output (peak force – F_p) at each time interval (T). The AC law is a difference equation whose parameters are designed to be dependent on the plant parameters (a_0,a_1,b_0,b_1); hence, AC law parameters are also adjusted right after the plant parameters are estimated. It is important to avoid drift in the estimation of the parameters in the recursive least squares algorithm. A typical adaptive pole placement control law is given as:

$$\begin{aligned} f_c(k) = {} & t_0 F_r(k-1) - [r_1 + b_1/b_0] f_c(k-1) \\ & - r_1 (b_1/b_0) f_c(k-2) \\ & - s_0 F_p(k-1) - s_1 F_p(k-2) \end{aligned} \qquad (2)$$

where t_0,r_1,s_0,s_1 are the control law parameters which are dependent on the plant parameters and desired control performance (Altintas 2012). There are various adaptive control methods, which give the same performance (Altintas 1994, 2012).

Adaptive Pole placement controller is experimentally tested in a slot milling operation where the axial depth of cut is varied stepwise, as shown in Fig. 2.

Adaptive Control, Fig. 3 Experimental results of adaptive control test



AC system is set to maintain the peak cutting forces at $F_r = 1{,}200$ N. The parameters of the machining process Eq. 1 are identified recursively from the present feed ($f_c(k)$) and the peak force measurement ($F_p(k)$) at time interval k; the controller parameters are adjusted, and new feed rate command is calculated from Eq. 2. The experimental results are given in Fig. 3. The system maintains the peak force at the desired 1,200 N by manipulating the feed. The parameters converge without any drift. However, there are severe overshoots each time when the depth of cut increases suddenly, because the CNC servo step drives cannot reduce the feed rates suddenly. AC systems can be most effective in machining dies, molds, and aerospace parts with sculptured surfaces where there is no step change in the depth of cuts. One of the main difficulties in using the AC systems is the lack of practical force sensors that can be used in industry.

Cross-References

▶ Computer Numerical Control
▶ Cutting Force Modeling

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Adaptronics

▶ Actuator

Additive Manufacturing Technologies

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Synonyms

3D printing; Layered manufacturing; Selective laser sintering; Stereolithography

Definition

Rapid Prototyping is the construction of complex three-dimensional parts using additive manufacturing technology.

Theory and Application

Introduction

Additive Manufacturing Technologies (AMT) are capable of building complex 3D objects by stacking up thin individual layers. By using this additive approach the degree of freedom regarding shape complexity is greatly enhanced compared to subtractive processes like turning or machining. AMT is largely used for manufacturing short-term prototypes (Rapid Prototyping), but it is also used for small-scale series production (Rapid Manufacturing) and tooling applications (Rapid Tooling). Besides applications in engineering, RP is becoming more and more popular in medical applications, where patient-specific geometries are required (e.g., orthopedics, dentistry, and hearing aids).

In order to achieve a good surface quality, thin layers are crucial. Modern RP techniques use layer thicknesses between 15 and 100 μm. Thinner layers lead to smoother surfaces, but usually also to slower build speeds. There is quite a large variety of RP processes available. Depending on the utilized feedstock (solids, powders, or liquids) a number of techniques, as described in the following chapters, can be distinguished.

Techniques Based on Solid Feedstock

Fused Deposition Modeling (FDM)

Description An extrusion head is used to heat a thermoplastic polymer filament and print each layer on the building platform (Fig. 1). During extrusion, the filament is in a semiliquid state and is positioned by the head's movement, according to the layer information of the CAD design. In many cases, there are two nozzles, one for the part and the other one for the support material. To facilitate the removal of the support, water soluble materials can be used. This RP process was developed by Stratasys Inc. in the early 1990s (Cooper 2001).

Material and Accuracy The available materials for FDM process are Acrylonitrile Butadiene Styrene (ABS), Poly-carbonate (PC)-ABS Blend, PC, and Polyphenylsulfone (PPSF) and polylactic acid (PLA).

The accuracy depends on the bead width, the gap between the bead and the layer thickness.

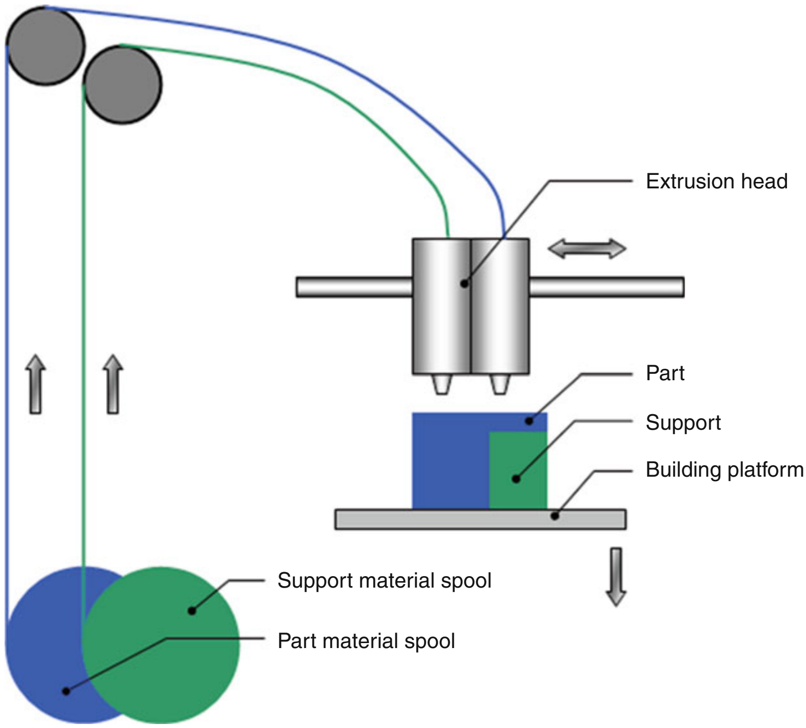
Application FDM parts were used for concept visualization, direct-use components, lost geometries for investment casting, and medical applications (Fig. 2).

Techniques Based on Liquid Feedstock

Stereolithography (SLA)

Description A UV laser, typically a solid state Nd-YAG laser, is deflected by a mirror scanning system according to the geometry of the CAD file (Fig. 3). Where the laser beam hits the resin surface, polymerization starts and solidifies the liquid resin. The building platform is lowered in z-direction for a new layer to form. Since the liquid resin is not capable of stabilizing geometries, the generation of support structures is necessary (Bartolo 2011).

Material and Accuracy The SLA process works with a layer thickness of 50–100 μm and



Additive Manufacturing Technologies, Fig. 1 Schematic of an FDM process

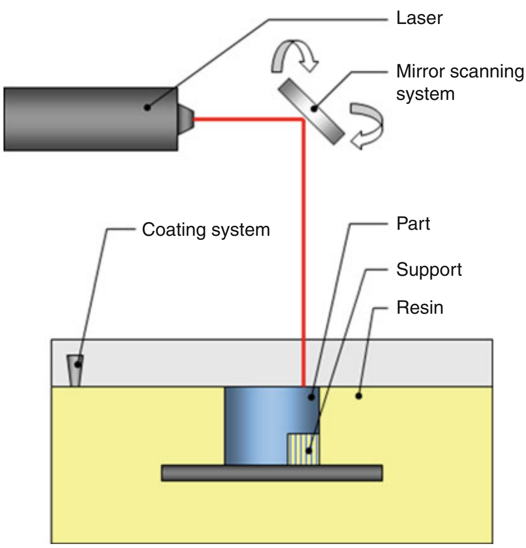
Additive Manufacturing Technologies, Fig. 2 HP Designjet 3D with a ball bearing (Material: ABS)

a scan speed of 500–1,000 mm/s. With an appropriate optical setup the layer thickness and feature resolution can be minimized down to 5 μm (mircoSLA). The used resin is a liquid UV-curable photopolymer (Liska and Stampfl 2010). By using a variant of SLA based on two photon polymerization (2PP), resolutions down to less than 100 nm are possible. In order to optimize form tolerances of microSLA computer tomography is used for the CAD model and tolerances smaller than 50 μm were achieved (Neumeister et al. 2012).

Application SLA parts were used for concept visualization, tooling, and investment casting (Fig. 4).

Digital Light Processing (DLP)

Description To reduce the price and increase the building speed, dynamic-mask-based stereolithography (DMS) has been developed. Instead of an expensive laser system with the row-by-row structuring, the process uses a projector with digital light processing (DLP) technology. Due to the fact that the whole layer is exposed in one step, the building speed does not depend on the geometry. The typical exposure times for each layer range from 3 to 12 s. The maintaining costs of the common used



Additive Manufacturing Technologies, Fig. 3 Schematic of a Laser-based SLA process

high-pressure mercury lamps are in comparison to UV laser systems fairly moderate.

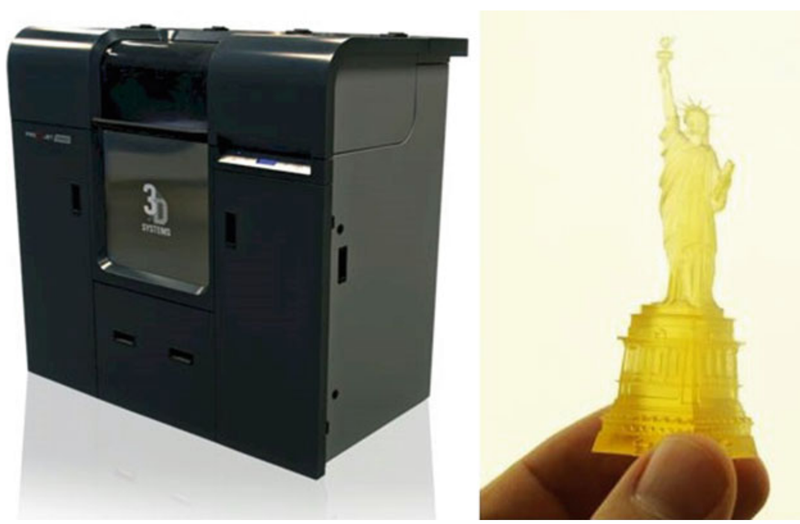
Recent developments use an LED array instead of high-pressure mercury lamp, the advantage of those arrays is a homogeneous and more powerful light. As can be seen from Fig. 3 the emitted light is selectively deflected by the micromirror array and white pixels lead to a solidification of the resin. The resin can either be exposed from below, as depicted in Fig. 5, or alternatively from the top.

Material and Accuracy At a given build volume, the achievable pixel resolution is given by the number of mirrors on the chip. For a system with 1,400 × 1,050 pixels and a targeted resolution of 50 μm, the build size is 70 × 50 mm. Typically, a liquid acrylate or epoxy-based photopolymer is used. Achievable layer thicknesses range from 10 to 100 μm.

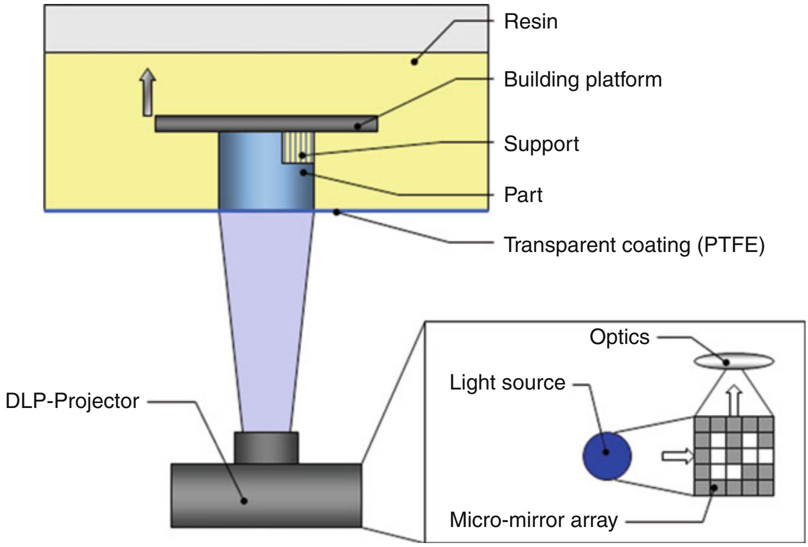
Application Due to the pixel resolution, the process is mostly used for small and delicate parts in the field of jewelry and medical applications (hearing aids), as you can see in Fig. 6.

Polyjet

Description In order to combine the advantages of inkjet-based and lithography-based



Additive Manufacturing Technologies, Fig. 4 3DSystems Projet 5000 with the statue of liberty (Material: 3DSystems VisiJet® MX)

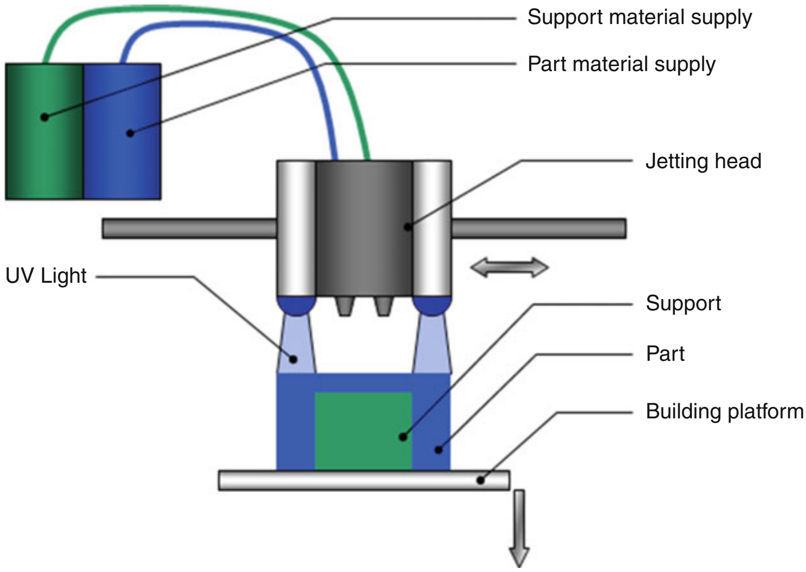


Additive Manufacturing Technologies, Fig. 5 Schematic of a Dynamic-mask-based SLA process

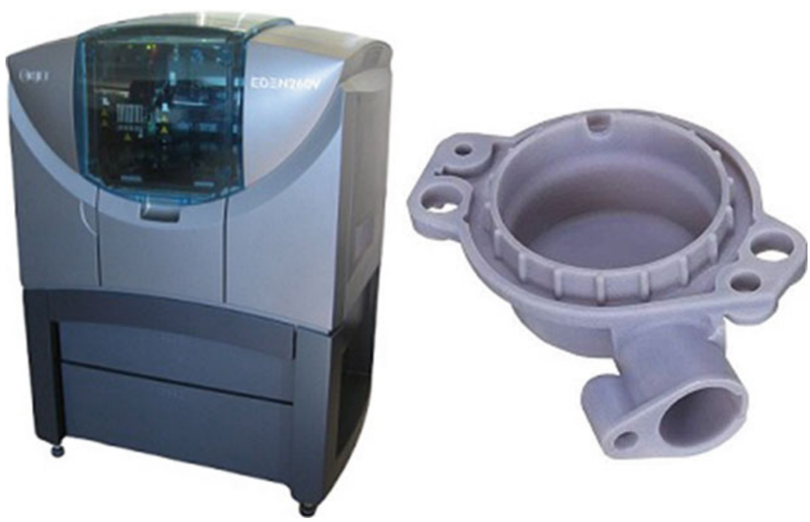
Additive Manufacturing Technologies, Fig. 6 Envisiontec Perfactory with a demonstration part (Material: Envisiontec R11®)

processes, systems have been developed, which are capable of processing liquid photopolymer using an inkjet head. During the motion of the head, nozzles eject small droplets of photopolymer and UV lamps solidify the material after deposition (Fig. 7). The inkjet head can deposit two types of material, the build and the support material. The support serves as a base for regions with overhangs and can be fully removed by water jets.

Material and Accuracy A typical resolution in the *xy* plane is around 40 μm and a layer thickness of down to 15 μm can be achieved. The support and build material are both UV-curable photopolymers, with the difference, that the support material can be jetted or scratched off easily and is soluble in alkaline solutions. By adding additional inkjet heads, multimaterial structures can be printed (e.g., with hard and soft regions within the part).



Additive Manufacturing Technologies, Fig. 7 Schematic of a POLYJET printing process



Additive Manufacturing Technologies, Fig. 8 Objet Eden 260v with a demonstration part (Material: Objet VeroBlue®)

Application Parts were used for concept visualization, functional prototypes, tooling, and investment casting (Fig. 8).

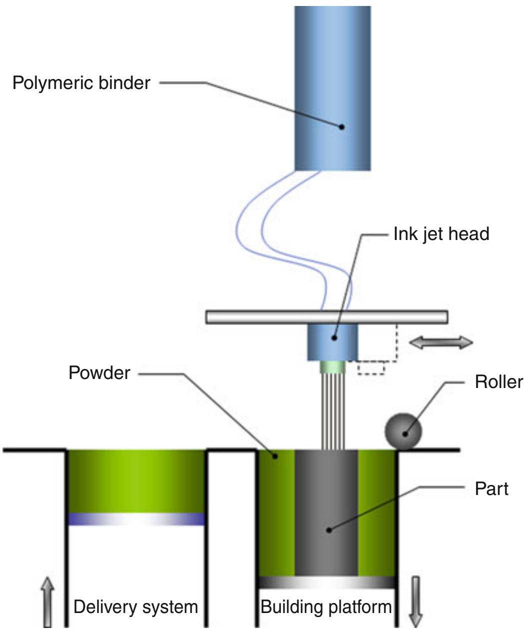
Powder-Based Techniques

3D Printing

Description The 3DP (Cooper 2001) is a process, where liquid binder is jetted into a powder bed, locally fusing the individual powder particles. A computer model is sliced into 2D profiles and printed successively on a powder layer until the whole part is finished. To complete the manufacturing process, the removal of unused powder and the infiltration of the part with additional binder are necessary (Lam et al. 2002).

In Fig. 9, the schematic of the 3DP process is shown. A roller coats the solidified area layer-by-layer with new material from the powder delivery system and the inkjet head structures each 2D pattern. The fabrication piston lowers a layer thickness after printing process (Cooper 2001).

Material and Accuracy The building speed (*z*-axis) depends on the size and complexity of the 2D pattern; typically values around 20–30 vertical mm/h are achieved. The process uses high-performance composite powder, based on starch or ceramic particles.



Additive Manufacturing Technologies, Fig. 9 Schematic of a 3DP process

Application The 3DP process is mainly used for concept models (Gebhardt 2008), as you can see in Fig. 10.

Selective Laser Sintering (SLS)

Description In Fig. 11, the principle of the process is shown: A galvanometric mirror system allows the beam to scan the whole building platform and thermally bond the particles together. The recoating process is equal to 3DP – a roll is used to coat the solidified area with new material. As energy source either high-power lasers or electron beams can be used.

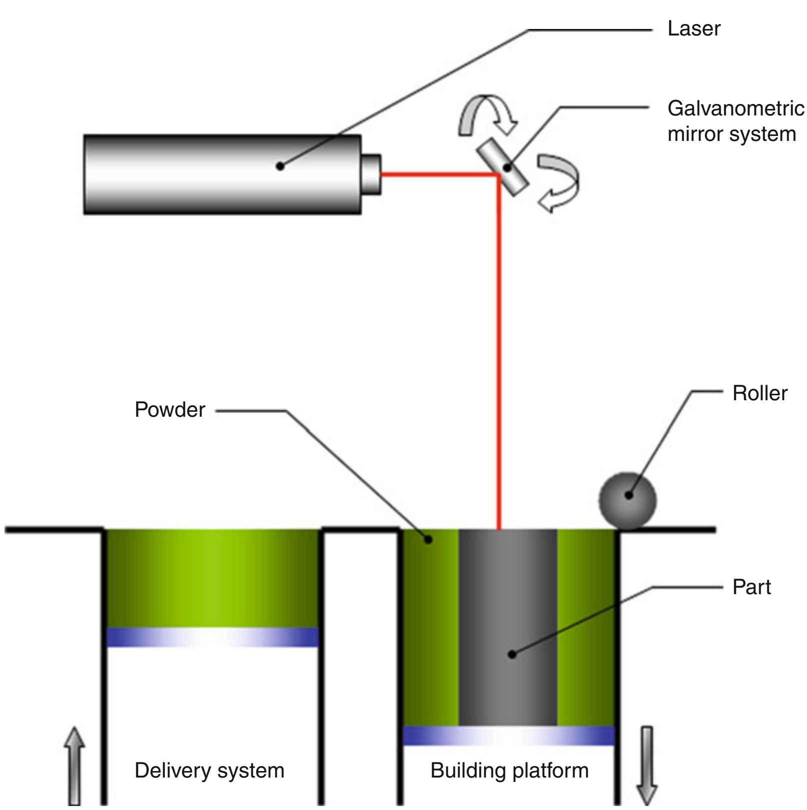
Selective Laser Melting (SLM)

In case of metals, it is common to use the term melting instead of sintering.

Material and Accuracy The accuracy of the process is defined by the layer thickness of 20–40 μm and the variable focus diameter of 100–500 μm (EOS EOSINT M280); fine details are limited to a thickness of 500 μm. SLS machines use metal-, polymer-, and sand powder.

Additive Manufacturing Technologies, Fig. 10 ZCorp ZPrinter 310 with a combustion engine (Material: ZCorp zp® 150)

Additive Manufacturing Technologies, Fig. 11 Schematic of an SLS process



Additive Manufacturing Technologies, Fig. 12 EOS EOSINT M280 with demonstration parts (Material: EOS MS1®)

Application Laser sintering processes are used for functional parts. Casting processes are possible, but the direct application is used more frequently (Fig. 12).

Cross-References

▶ Prototyping

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Adiabatic Shearing in Metal Machining

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Synonyms

See Definition: Extended Definition

Definition

Adiabatic shearing in metal machining is plastic straining to form a chip so quickly that the heat generated has no time to flow away. If the heating causes the metal to soften (overcoming the strain hardening), further straining may concentrate in the soft part so that it becomes even hotter and softer. Shearing becomes localized in a narrow band of increasingly hot metal.

Extended Definition

Strain softening, shear localization, and shear banding are all associated with adiabatic shearing, but they are not synonyms as they can also occur, for other reasons, in isothermal conditions.

Shear localization or banding due to thermal softening does not require truly adiabatic (i.e., no heat flow) conditions. All that is required is a condition in which enough heating occurs. The term catastrophic thermal shear covers this. It focuses more on the observed behavior, less so on its cause. Catastrophic thermal shear leads to chips with a segmented or serrated or sawtooth form when viewed from a direction normal to the cutting tool's cutting edge (see Application for examples). It is theory and applications of shear localization, leading to segmented, serrated, or sawtooth chip formation, that is the subject of this entry.

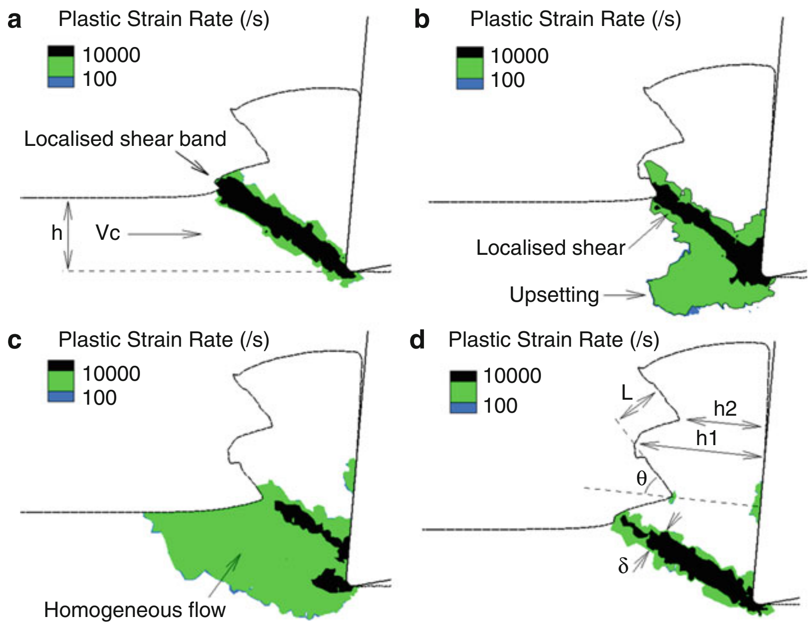
Theory and Application

The kinematic and geometrical conditions of serrated chip formation are more complex than those of deformation in simple shear, torsion, compression, and punching tests that are commonly used to study adiabatic shearing fundamentals. Figure 1 shows a cycle of flow during serrated chip formation from (a) localized shear in a shear band to (b) mixed localized flow and upsetting (upsetting is needed to accommodate the displacement of the cutting edge into the work material as the shear band moves up the rake face), to (c) homogeneous flow as the shear band moves out of the chip formation region (the shear band is deformation rather than load driven), and to (d) localized flow again (h is the uncut chip thickness, v_c the cutting speed).

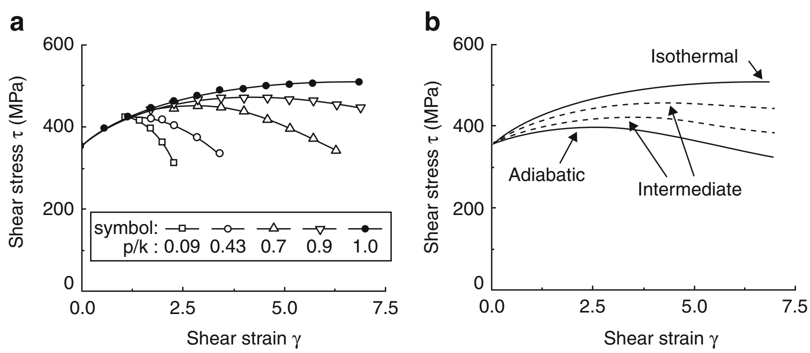
The role of theory is to determine the conditions of h, v_c, tool geometry (rake angle), and work material thermo-physical-mechanical properties that give rise to serrated rather than continuous or other classifications of chips and, in the conditions of serrated chip formation, to predict such measurable features of the serration as the maximum and minimum chip thickness h_1 and h_2, the angle θ at which the saw teeth are inclined to the back face of the chip, the teeth face separation L, and the shear-band width δ. If such quantities are predicted, then the cycles of temperature and stress in the tool will also be known.

Critical Conditions for Shear Localization

Strain softening is necessary for shear localization to occur but is not always due to adiabatic shear. Figure 2a, b show example dependencies



Adiabatic Shearing in Metal Machining, Fig. 1 Numerical simulation of serrated chip formation at relative displacement intervals (**a**–**d**) of the work toward the tool of 0.5 h, from the author's work. The particular strain-rate values are associated with h = 0.1 mm and $v_c = 50$ m/min



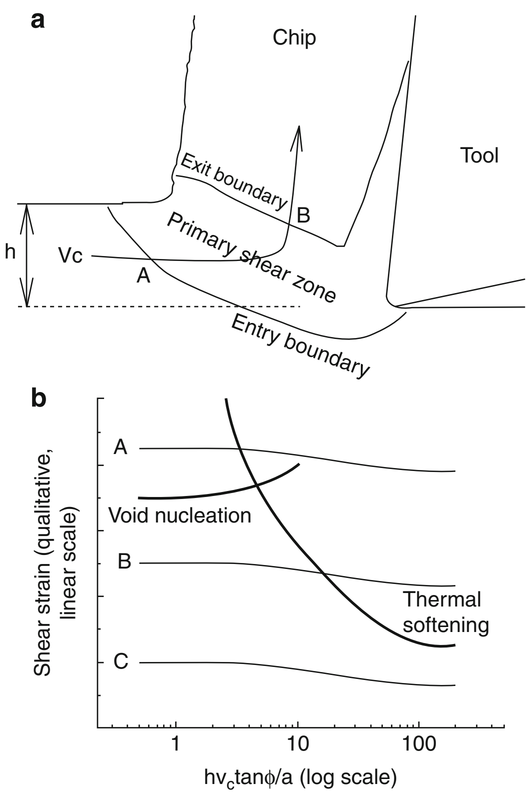
Adiabatic Shearing in Metal Machining, Fig. 2 The influences of (**a**) imposed pressure and (**b**) heating on a metal's stress versus strain behavior (example of a low carbon re-sulphurized steel)

of shear stress τ on shear strain γ from simple shear tests. The data are from tests on a free-machining mild steel but are intended to be considered qualitatively. In both figures, strain hardening at low strains gives way to strain softening at higher strains.

In Fig. 2a, from data in Shaw (2004), the test conditions are at room temperature and low strain rate. Conditions are isothermal, and strain softening is due to the nucleation and growth of voids. The different curves result from applying compressive pressure p to the shear plane. The larger the ratio p/k, where k is the peak shear flow stress from the test, the larger is the strain γ at which $d\tau/d\gamma = 0$.

Figure 2b considers the effect of heating on the stress–strain curve. The curve marked "isothermal" is that for p/k = 0.6 from Fig. 2a. That marked "adiabatic" is obtained from the isothermal curve assuming all of the plastic work is converted to heat and that the shear flow stress reduces with temperature rise at the rate of 30 MPa per 100 °C (a reasonable value). The two curves marked "intermediate" suppose one third and two thirds of the heat to be conducted away. In these cases, softening is the result of heating. The strain at which $d\tau/d\gamma = 0$ increases from the adiabatic to the isothermal condition.

As has already been written, the conditions of serrated chip formation are more complicated



Adiabatic Shearing in Metal Machining, Fig. 3 (**a**) Continuous chip formation; (**b**) shear strain dependencies on thermal number, *thick lines* for the initiation of shear localization due to void nucleation and thermal softening, and *thin lines* A to C for different circumstances of continuous chip formation considered in main text

than those of simple shear. Even continuous chip formation (Fig. 3a) is more complicated than simple shear. In the primary shear zone of a continuous chip, strain increases along a streamline, for example, from A to B, so strain softening is most likely at the exit boundary. Along the exit boundary, both temperature and pressure vary. Small amounts of softening can be supported, without a change from continuous to banded flow, by hydrostatic pressure variations in the flow field. If shear localization does develop, it will occur during the buildup to continuous chip formation, not after the steady state has been established. Nonetheless, the conditions in which a continuous chip flow gives way to shear localization can be qualitatively considered in terms of the material behavior shown in Fig. 2 (assuming localization to set in when $d\tau/d\gamma \approx 0$) and the flow field of continuous chip formation.

Theories of heating in metal cutting show that conditions in the primary shear zone of a continuous chip change from isothermal to adiabatic as the thermal number $hv_c\tan\varphi/a$ increases through the range ≈1–100 where φ is the shear plane angle and a is the thermal diffusivity (the ratio of thermal conductivity to heat capacity) of the machined material. In Fig. 3b, the critical strains from Fig. 2 at which $d\tau/d\gamma = 0$ are plotted against the thermal number. Although the strain axis could have been labeled from 0 to 10, from the data in Fig. 2, numbers have been omitted because it is intended that the figure's use be qualitatively generalized beyond its particular example. At low values of the thermal number (isothermal conditions), critical strains are due to void nucleation and growth. As the number increases through the range ≈10–100, thermal softening becomes the critical factor. Critical strains for void nucleation vary with pressure (Fig. 2a), but only one level is shown in Fig. 3b.

Figure 3b also includes, as the dashed lines, the variation with thermal number of a range of possible variations of shear strains associated with continuous chip formation. For case A, these strains are greater than the critical strains for shear localization at all values of the thermal number. With increasing magnitude of the product hv_c, a transition will occur from serrated or sawtooth chip formation resulting from instability due to void formation to such chips caused by thermal instability. In case B, a change from continuous to serrated chip formation will occur as the thermal softening boundary is crossed. In case C, serrated chip formation will not occur at any value of hv_c.

Observed dependencies of the critical hv_c combinations for the onset of adiabatic shear banding on the material being machined and the tool geometry may be considered in terms of Fig. 3b. Observed transitions to localized shear and serrated chip formation with increasing h and v_c are only likely to be due to increasingly adiabatic conditions if $hv_c\tan\varphi/a$ is in the range ≈10–100. Certainly any transition at $hv_c\tan\varphi/a$

<1 or >100 is unlikely to be the result of adiabatic shear. Heat treatments that increase machined material hardness and reduce strain hardening, or prior working that also reduces strain hardening, will reduce the process strain at which thermal softening occurs and will reduce the critical values of h and v_c for serrated chip formation. Reducing the tool rake angle will increase the strain level of continuous chip formation and thus will also reduce the critical values of h and v_c at which serrated chips occur.

Developing a quantitative theory of the conditions for shear localization is the subject of ongoing numerical (finite element-based) research. Key earlier papers are (Recht 1964) in which the instability criterion $d\tau/d\gamma = 0$ was first applied, (Semiatin and Rao 1983) in which it was argued that $d\tau/d\gamma$ needed to be substantially negative and (Hou and Komanduri 1997) in which the complexities of temperature distributions in shear localized chips were examined in more detail than in previous work. Adiabatic shearing has been the subject of a number of general reviews, for example, Walley (2007), and books, for example, Bai and Dodd (1992). These mention but do not have a main focus on machining. Walley (2007) mentions nine earlier reviews.

Development of Shear Localization

Once shear localization is initiated, flow of heat from the shear band is predominantly normal to its surface. From the theory of heat diffusion and given that a shear band is active (Fig. 1) for a time $\approx(h/v_c)$, the minimum width over which conditions may be considered adiabatic $\approx(a[h/v_c])^{0.5}$ This is expected to be the minimum width δ of an adiabatic shear band, or $(\delta/h)_{min} \approx(a/[hv_c])^{0.5}$. For typical machining conditions, δ_{min} is of the order of 10 μm. Experiments generally do show δ to be of this order and reducing with reducing h/v_c but not always to the power of 0.5.

Furthermore, δ depends on material properties in addition to a. δ may not achieve its minimum value. The thinning of a shear band is driven by the slope of the strain-softening curve. This varies widely between metals. Microstructural transformations, for example, dynamic recrystallization and phase changes (e.g., ferrite to austenite transformations in steels or α to β transformations in Ti alloys), greatly affect softening behavior and are observed in the shear bands of serrated chips at high cutting speeds. A metal's softening response as well as its thermal diffusivity determines its shear-band thickness.

How the homogeneous deformation (Fig. 1c) develops between shear bands, in response to the stresses acting on it from the just formed shear band and from the tool, determines segmentation shape – such dimensions as h_1, h_2, L, and θ. Softening in the shear band thus influences segmentation shape as well as shear-band thickness.

Quantitative modeling and simulation of all these matters is the subject of ongoing research and cannot be sensibly reviewed in a short entry such as this.

Applications

Table 1 lists, for a range of metals of interest to machining and from published literature, experimentally observed minimum values of the product of h and v_c for serrated chip formation due to adiabatic shear localization. They are to be regarded only as indicative as in fact they depend on rake angle, a factor not considered in collecting material for the table and on material heat treatment, sometimes not recorded in the literature. Furthermore, transitions from one chip form to another are not sharp.

Although the minimum values of hv_c range from <100 to $>1{,}000$ mm^2/s, when divided by thermal diffusivity a, a narrower range of 20–100 is obtained. Considering that typical values of continuous chip shear plane angle are 20–40°, $hv_c\tan\varphi/a$ values are in the range expected from Fig. 3b.

In practice, the ranges in Table 1 are so broad that machinists or other interested people with a particular need to know the transition to adiabatic shearing for a particular work material heat treatment and tool geometry would be well advised to carry out their own experiments, for example, varying cutting speed over their range of interest at a fixed uncut chip thickness.

However, some guidelines can be given in terms of Fig. 3b's three cases A to C.

α and α-β titanium alloys almost always follow case A behavior although a small number of exceptions (case B behavior) may be found. Figure 4 shows a change from irregularly (void nucleated) to regularly (adiabatic sheared) serrated chips for a Ti-6Al-4V alloy as hv_c increases.

Adiabatic Shearing in Metal Machining, Table 1 Minimum values of hv_c for serrated chip formation by adiabatic shearing

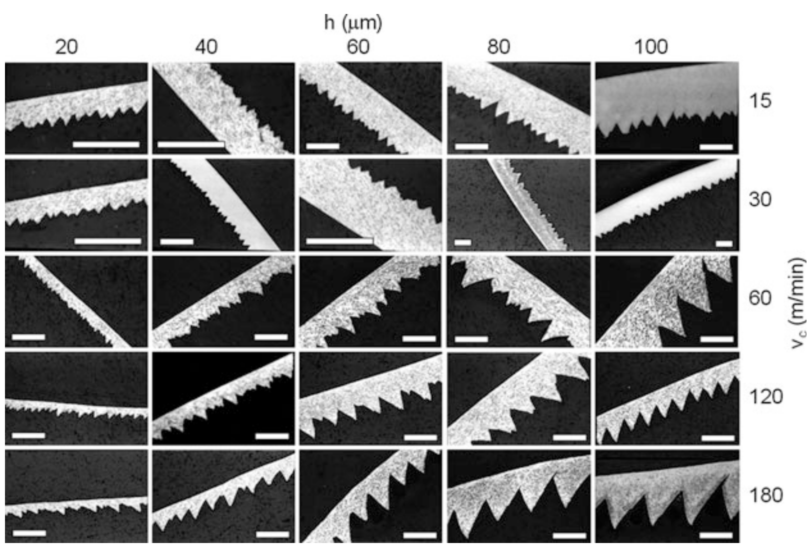
Metal	≈ $(hv_c)_{min}$ (mm^2/s)[a]	Representative a (mm^2/s)	hv_c/a
Ti-6Al-4 V	70–150	3.5	20–40
Inconel 718	100–170	3.5	30–50
AISI 1045 steel: Q&T HRC50	300–330	15	20–22
AISI 1045 steel: Q&T HRC35	430–480	15	29–32
AISI 1045 steel: normalized	1500[b]	15	100
Austenitic stainless steels	100–300	4	25–75
AA7075-T651	700–1,000	60	12–17

[a]To convert to the more practical (mm)x(m/min) unit, multiply by 0.06
[b]Limited data

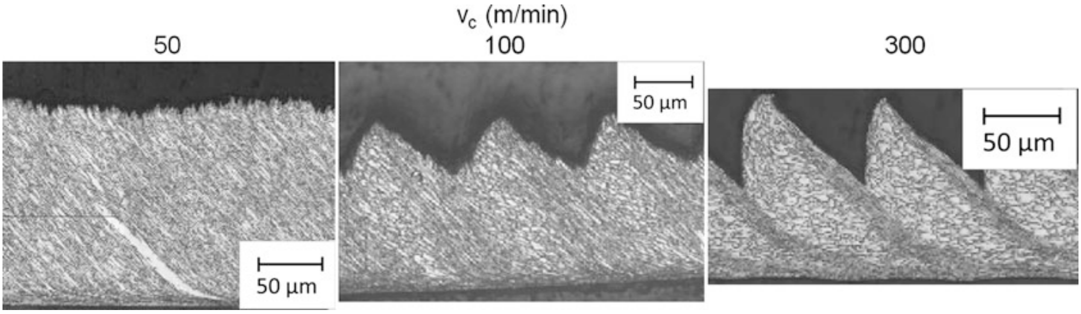
By contrast, nickel-base superalloys and ferrous alloys almost always show case B behavior (with zero or negative rake tools, behavior can change to type C with increasingly positive rake angle). Figure 5 shows changing chip form from continuous to serrated with increasing speed for an Inconel 718 alloy, while Fig. 6 shows forms obtained for an AISI 1045 steel quenched and tempered to HRC50. In Fig. 5, the shear bands show deformed microstructure up to the highest speed, but in Fig. 6, a transformed shear band is seen at $v_c = 240$ m/min.

Finally, aluminum alloys show highly variable responses. Behavior of a single composition can vary from case A to case C dependent on heat treatment. Figure 7 shows overaged and underaged AA7075 chips. The overaged chip is continuous even though $hv_c \tan\varphi/a > 100$ (type C). The underaged chip is serrated. It maintains this to the lowest cutting speeds (type A).

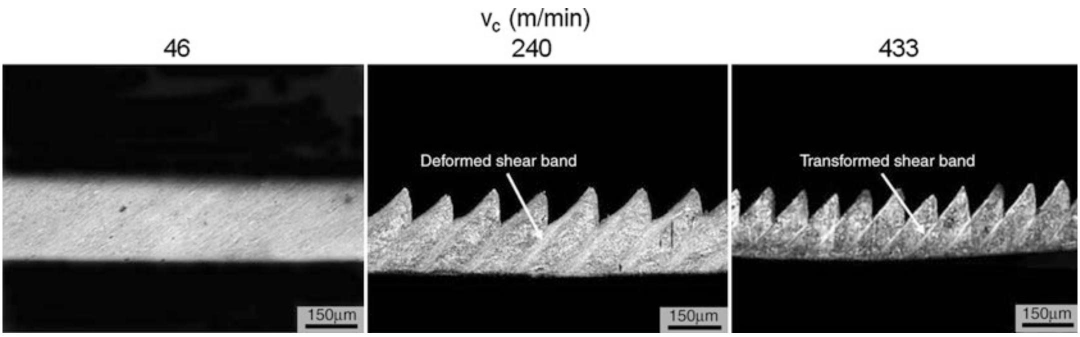
More examples can be found in two textbooks, Shaw (2004), which takes the view that fracture (void nucleation) is more important than adiabatic shear for the initiation of serrated chip formation, and Trent and Wright (2000), which considers secondary shear (stick–slip motion between the chip and tool) as additionally influencing behavior, and one research monograph (Tönshoff and Hollmann 2005).



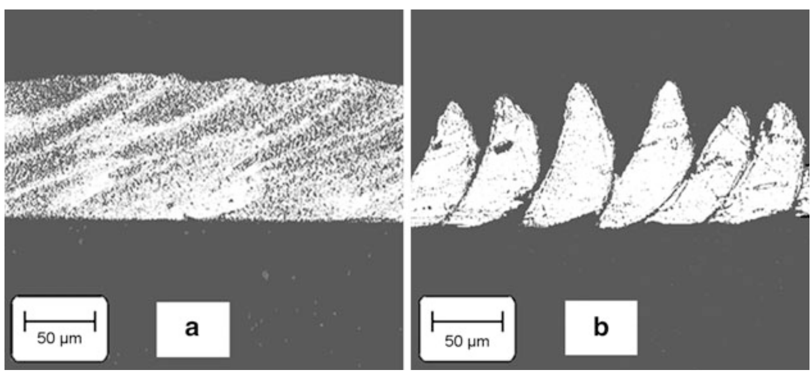
Adiabatic Shearing in Metal Machining, Fig. 4 Chip forms for a Ti-6Al-4V alloy, tool rake angle −6°, and scale bars 100 mm (From original work of J. Barry, see Acknowledgments)



Adiabatic Shearing in Metal Machining, Fig. 5 Chip forms for Inconel 718, tool rake angle −6°, and h = 0.07 mm (From original work of E. Uhlmann and R. Zettier, see Acknowledgments)



Adiabatic Shearing in Metal Machining, Fig. 6 Chip forms for AISI 1045 steel, HRC50, tool rake angle −10°, and h = 0.15 mm (From original work of C.Z. Duan and L.C. Zhang, see Acknowledgments)



Adiabatic Shearing in Metal Machining, Fig. 7 Chip forms for AA7075 v_c = 7,000 m/min and tool rake angle 0°: (**a**) overaged, h = 0.14 mm and (**b**) underaged, h = 0.07 mm (From original work of C. Mueller, see Acknowledgments)

Acknowledgments I wish to thank the following people for making available chip section pictures from their original work and allowing me to include them in this entry: J. Barry (Element Six), Figure 4; E. Uhlmann and R. Zettier (Technical University of Berlin), Figure 5; C.Z. Duan and L.C. Zhang (University of New South Wales), Figure 6; and C. Mueller (Technical University of Darmstadt), Figure 7. In addition, the sections in Figures 5 and 7 have appeared as parts of other figures in Chs. 18 and 15, respectively, of Tönshoff and Hollmann (2005).

Cross-References

▶ Chip-forms, Chip Breakability and Chip Control
▶ Cutting of Inconel and Nickel Base Materials
▶ Cutting Temperature
▶ Cutting, Fundamentals
▶ Hard Material Cutting
▶ High Speed Cutting

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Adjustable Manufacturing System

▶ Flexible Manufacturing System

Adjustable Manufacturing/ Production

▶ Changeable Manufacturing

Advanced Ceramic

▶ Ceramic Cutting Tools

Advancement

▶ Optimization in Manufacturing Systems, Fundamentals

Aerostatic Bearing

▶ Bearing

Agent Systems

▶ Agent Theory

Agent Theory

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Synonyms

Agent systems; Agent-based computing; Autonomous agents; Multi-agent system

Definition

Agent theory provides the basis for a novel paradigm of computation. While agent-based computing (or simply, agent system) has several roots as far as its concepts, models, and enabling technologies are concerned, there is a general consensus about its two main abstractions (Wooldridge 2009; Luck et al. 2005; Shoham and Leyton-Brown 2009):

- An **agent** is a computational system that is situated in an unpredictable, dynamic environment where it is capable of exhibiting autonomous and intelligent behavior.
- An agent's environment typically includes also other agents with diverging information and/or interests. The community of interacting agents, as a whole, operates as a **multi-agent system** (MAS) that can solve such complex problems that are beyond the limits of individual agents.

Theory and Application

History

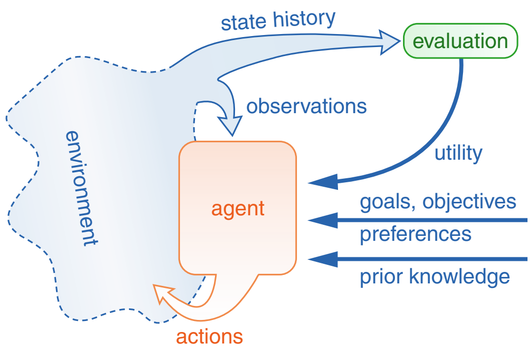
The theory of computational agents goes back at least a quarter of a century when research in distributed artificial intelligence had been initiated. Agents made the real breakthrough in the 1990s when the emphasis in mainstream research shifted: the focus on logic was extended and attention changed from goal-seeking to rational behavior, from ideal to resource-bound reasoning, from capturing expertise in narrow domains to reusable and sharable knowledge repositories, and from the single to multiple cognitive entities acting in communities (Russell and Norvig 1995). These developments also coincided with the evolution of network-based computing technology, the Internet, mobile computing, the ubiquity of computing, as well as novel, human-oriented software engineering methodologies (Luck et al. 2005). All these achievements led to what is considered now the agent paradigm of computing.

Characterization of Agents

An agent operates in an **environment** from which it is clearly separated (see Fig. 1). Hence, an agent makes observations about its environment, has its own knowledge and beliefs about its environment, has preferences regarding the states of the environment, and finally, initiates and executes actions to change the environment. Agents operate typically in environments that are only partially known, observable, and predictable. **Autonomous** agents have the opportunity and ability to make decisions of their own. **Rational** agents act in the manner most appropriate for the situation at hand and do the best they can do for themselves. Hence, they maximize their expected utility given their own local goals and knowledge. Rationality can be bound by the computational complexity of a decision problem, the limitation of computing resources, or both. An agent with optimization objectives but with limited means is a **bounded rational** agent. A **reactive** agent responds in timely manner – in real or near time – to changes of its environment, while a **proactive** agent is able to act in anticipation of future situations and goals.

As for their key common properties, computational agents:

- Act on behalf of their designer or the user they represent in order to meet a particular **purpose**.



Agent Theory, Fig. 1 The agent and its environment (After Russell and Norvig 1995)

- Are **autonomous** in the sense that they control both their internal state and behavior.
- Exhibit some kind of **intelligence**, from applying fixed rules to reasoning, planning, and learning capabilities.
- **Interact** with their environment and, in a community, with other agents.
- Are, ideally, **adaptive**, i.e., capable of tailoring their behavior to the changes of the environment without the intervention of their designer.

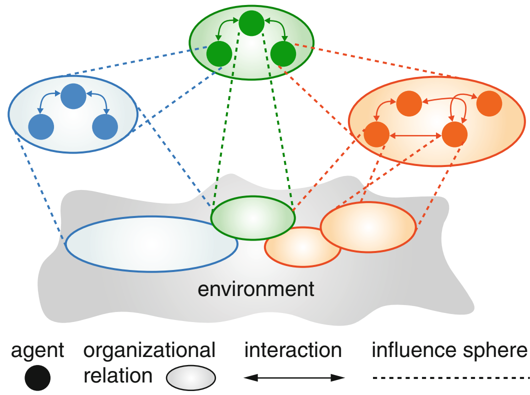
Further agent properties, characteristic in particular domains and applications, are **mobility** (when an agent can transport itself to another environment to access remote resources or to meet other agents), **genuineness** (when it does not falsify its identity), **transparency**, and credibility or **truthfulness** (when it does not communicate false information willfully). Even though they exhibit only some of the above properties, agents relax several strong assumptions of classical computational intelligence: they typically have incomplete and inconsistent knowledge as well as limited reasoning capabilities and resources.

Multi-agent Systems

In a multi-agent system (MAS), the decisions and actions of various agents do necessarily interact. However, just due to **interaction**, a multi-agent system can occasionally solve problems that are beyond the limits of the competence of the individual agents and/or may exhibit **emergent behavior** that cannot be derived from the internal mechanisms of the components. In a community an agent has to **coordinate** its actions with those of the other agents, i.e., to take the effects of other agents' actions into account when deciding what to do. Coordination models provide both **media** – such as channels, blackboards, pheromones, and market – and **rules** for managing the interactions and dependencies of agents. Coordination requires some regulated flow of information between the agent and its surrounding environment, i.e., **communication**. In a MAS, coordination is possible both by indirect communication via the environment and by direct information exchange between specific agents. In any case, communication needs some **language**(s) with syntax and semantics, at least partially known for each communicating agent.

Collaboration means carrying out concerted activities so as to achieve some shared goal(s). For instance, in a scheduling domain machine agents may agree on executing each task of a job with the aim of completing an order by the given due date. The shared goal (completing an order) can be achieved only if all agents commit themselves to carrying out the actions they have agreed upon. In general, in a MAS of self-interested and autonomous agents, meeting high-level objectives and satisfying system-wide constraints need **cooperation**, an interactive relationship that makes it possible to harness knowledge of other agents or to make use of their actions in the service of joint interests. The basis of any form of cooperation is reciprocity and trust between autonomous parties who can decide and act in their own right. Cooperation is the alignment of various, possibly even disparate goals in the hope of some mutual benefit. Cooperation can be developed among interrelated parties who have their own identity and discernible interests (expressed in terms of goals, objectives, utility or profit, etc.), who have the faculties for pursuing their own interest, and who admit to the autonomy of other related parties. Cooperation has a number of forms in the physical and biological world and is the prime basis of processes, organizations, and institutions of human society (Axelrod 2006).

The overall operation of a multi-agent system is affected by an **organization** that is imposed on



Agent Theory, Fig. 2 Generic scheme of a multi-agent system (After Jennings 2001)

the individual agents. Even though there may be no global control or centralized data, and the computations are asynchronous, some organizational rules always exist. The organization determines the "sphere" of the activity of agents, as well as their potential interactions (see Fig. 2).

The various organization patterns of multi-agent systems, such as teams, coalitions, markets, as well as hierarchic and heterarchic (including holonic) architectures, provide different ways to achieve system-wide design objectives and/or to facilitate the emergence of desired properties in multi-agent systems.

Agent Technologies

Agent-Level Decision Making

Depending on the actual problem and available knowledge at hand, agents can apply various **faculties of problem solving**, including searching, reasoning, planning, and learning. The notion of agents has a strong synthesizing power; hence, the applied techniques may include both symbolic and sub-symbolic methods, classical and quantitative decision theory, as well as knowledge-based reasoning and sophisticated belief-desire-intention (BDI) models. There are several approaches for realizing agents:

- Following the principles of classical **decision theory**, an agent makes choices from a set of alternative actions so that it can maximize the expected utility of its decisions. If a utility function or the required input data are not available, qualitative models are applied that work with preferences.

- An agent may have explicit knowledge of how its actions can change the states of its environment. Given some states to achieve – so-called **goals** – the reasoning over future courses of actions is a key to intelligent behavior. Artificial intelligence provided a host of **planning** methods to solve this problem under various assumptions.
- The decision problem of an agent can be cast in terms of cognitive concepts, such as knowledge and belief, desires and goals, and plans and intentions. A BDI agent is continually updating its beliefs based on perceptions, using its beliefs to reason about possible plans, committing to certain intentions, and realizing these intentions by acting. Agents who are situated in a dynamic environment can benefit from having **plans** which, on the one hand, can constrain the amount of reasoning and, on the other hand, can make coordination possible.

Interaction

Agents necessarily **interact** with each other – either indirectly, via the environment, or by direct communication. The various coordination and cooperation mechanisms range from emergent methods (without explicit communication among agents) to coordination protocols, coordination media, and distributed planning (Luck et al. 2005). A **coordination media** provides a shared memory space for communicating data in an asynchronous way. Typical examples are blackboards, pheromones in stigmergy-based coordination, or attraction-repulsion field. **Coordination protocols** control the interactions of agents in order to reach common decisions. For instance, a widely used protocol is the **contract net protocol** where a manager agent makes arrangements via bidding to have some task performed by one or more other agents. Goal-oriented agents forming a community may have disparate and conflicting goals. For resolving conflict situations, various negotiation mechanisms were developed, including auctions, one-to-one negotiation, bargaining, and argumentation-based negotiation (Wooldridge 2009). Collaborative acting and planning involve the intentions of multiple agents. Since the presence of other agents is always a source of uncertainty (beyond other possible sources), collaboration requires an integrated treatment of the beliefs and intentions of the agents who may take part in a collaborative act. That is why the BDI model provided the theoretical basis for **agent communication languages** (ACL), including the widely used Foundation for Intelligent Physical Agents standard (see FIPA). Communication and interoperability requires consensual knowledge of a community. A so-called **ontology** is an explicit specification of the conceptual structures of a given domain. It is usually expressed in a logic-based language that makes it possible to distinguish classes, instances, properties, relations, and functions in a clear-cut, consistent way. Consensual means that the whole community has a common understanding both on the content and form of the expressed knowledge. Ontologies also can facilitate machine processing, automated reasoning, as well as the interoperability of different agents.

Organization

Like any community, a MAS is formed by agents that are aimed at achieving some purposes, be them individual, system-wide or both. It is no wonder that multi-agent systems adapt all the basic human organization patterns. There are a number of organization structures that define various patterns of decomposing work, assigning responsibilities to those who do the work, as well as collecting and combining results. A particular organization structure comes together with rules concerning the conditions of participating in a MAS, the assignment of the roles and relations, as well as the use of protocols – all of which together realize a particular **coordination mechanism**. In a MAS, however, human organizational models can be surpassed. The ideas of decentralized problem solving, including the resolution of the conflict between individual and collective good, are widely studied in a number of other disciplines, such as economics, game theory, political science, biology, and ecology. Computational models of agency borrowing analogies from these fields are similar in that they rely on some form of **self-organization**. No central control is exercised, and the systems adapt their structure and functionality to the changing requirements and environmental conditions. Typically, members of the systems are individually able to achieve simple tasks, but their interactions lead to the **emergence** of complex collective behavior (Ueda et al. 2001).

Use of Agents

Agent technology and multi-agent systems, together with their supporting information and communication technologies – such as networking, software engineering, distributed and concurrent systems, mobile technology, electronic commerce, interfaces, semantic web, and cloud computing – have found their way to application and deployment in many fields. The key success factors behind the use of agents are as follows (Luck et al. 2005; Monostori et al. 2006):

- Agents provide a new **design metaphor** for structuring knowledge (and system design, accordingly) around components that have autonomy and capability to communicate. Objects that earlier had complex properties can now be personified. Further to procedures, abstract data types, and objects, agents as intentional entities represent an increasingly powerful abstraction of computing. Any kind of intelligence requires the handling of **conflicts** rooted in disparate interests. Conflicts become explicit if the system is modeled like a community of self-interested agents. Hence, the agent-based approach forces the system's designer to find ways for managing conflicts.
- Agents and MAS provide a wide array of models, techniques, formal modeling approaches, and development methodologies that all together shape general-purpose techniques of **agent-oriented software engineering** (AOSE) (Jennings 2001; Bordini et al. 2009). There have been developed several programming languages and software development environments which not only support MAS programming but also implement key concepts of MAS in a unified framework.
- Agent-based modeling is especially suitable for **simulating** the behavior of complex systems operating in dynamic environments. In contrast to traditional, top-down approaches, the emphasis is on capturing the individuals, together with all their limitations and interactions. The question is whether and how local interactions can produce observable – and useful – patterns of global behavior. Hence, **agent-based simulation** (ABS) became an accepted methodology for developing plausible explanations for emergent phenomena. Alternatively, it was used for verifying multi-agent system design in a number of fields from engineering to natural and social sciences (Gilbert 2008).

Agent-based systems can be realized in a wide spectrum: from so-called coarse-grained agents (like BDI) with sophisticated communication, cognitive reasoning, and learning faculties up to fine-grained agents with a very limited operational repertoire but high connectivity and intensive interactions. It is a general observation that fine-grained but complex systems may display patterns of behavior and develop certain functional properties that cannot be understood and explained solely on the basis of the control of the individuals. In the eye of the observer, these emergent features are unexpected, novel and show the traces of a stable order. Analysis of such systems leads to the terrain of **network theory**.

Agents in Manufacturing

Enterprises always operated within the fabrics of economy, society, and the ecosystem. In this complex, ever-changing, dynamic, and hardly predictable environment, manufacturing enterprises compete not only individually but also as members of various networks. No wonder that manufacturing called for new, more robust, adaptable, fault-tolerant, decentralized, and open organizational structures even before the paradigm of agent-based computing and MAS appeared (Hatvany 1985). Agent theories were really welcome because they helped to realize important properties as autonomy, responsiveness, redundancy, distributedness, and openness. Hence, many tasks related to manufacturing – from engineering design to supply chain management – have been to assigned to agents, small and large, simple and sophisticated, and fine- and coarse-grained, that were enabled and empowered to communicate and cooperate with each other (Monostori et al. 2006; Shen et al. 2006; Váncza et al. 2011).

Agents in Engineering Design and Collaborative Engineering

While design activities in various branches of engineering (mechanical, electrical, control, software, communication, etc.) are now being more and more integrated, **concurrent engineering** embraces all the main life-cycle activities such as marketing, product design, manufacturing, distribution, sales, operation, maintenance, disposal, and recycling. Customers are involved in production from the decisive moment of the conception of ideas, already in the design of the product they are going to purchase. With the pervasive connectivity of the Internet, personalization has been increasingly adopted for consumer products.

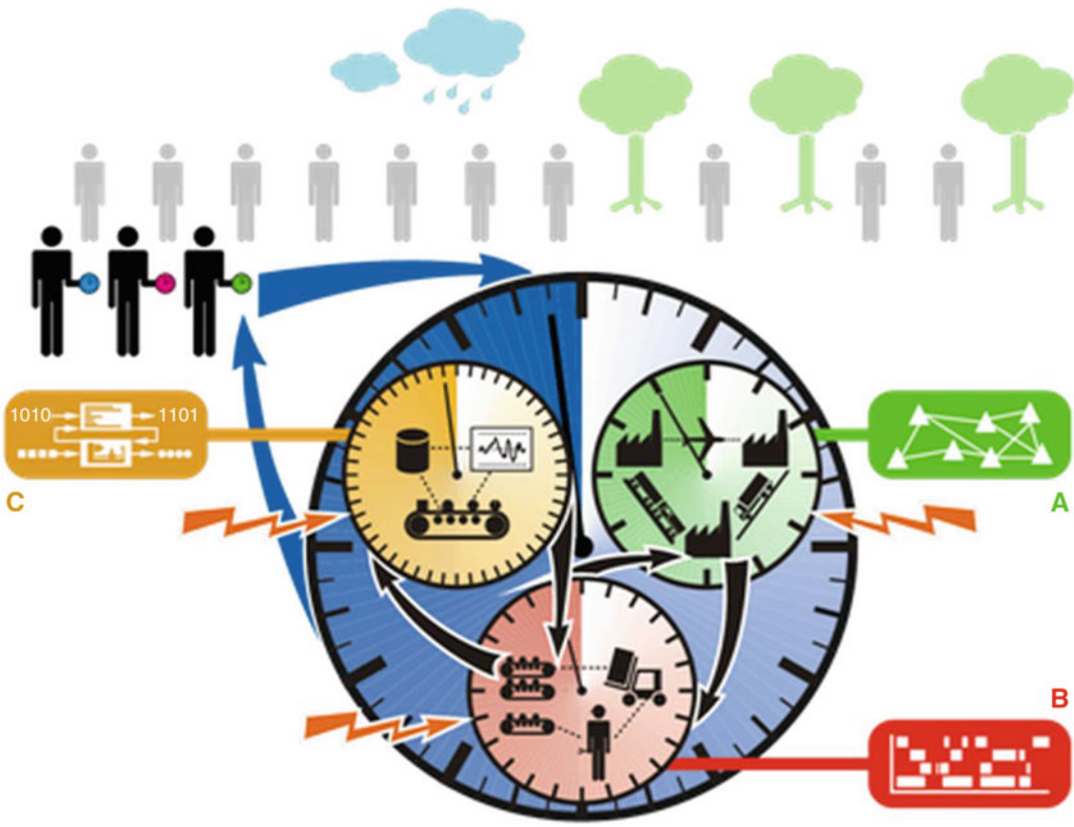
In a MAS design problems and the available knowledge can be structured in appropriately distributed ways. Collaborative and concurrent approaches to design are successful in particular because they are utterly based on **interaction** that helps harness external knowledge that could not have been captured and internally represented. Furthermore, collaborative engineering makes explicit the disparate goals, objectives, priorities, and concerns – in short, interests – of the various stakeholders related to a product's life cycle. These interests manifest themselves as conflicts just in the early phase of design when decisions with far-reaching effects are made. Negotiation over conflicts can drive the design process towards innovative solutions (Lu et al. 2007). A trade of incomplete knowledge against interest can be very fruitful: rational, interest-seeking behavior on the part of autonomous agents can result in successful overall performance even in cases when the agents have limited capabilities (knowledge and/or resources). At the same time, collaboration rests upon interaction, which is still the key to creative design.

Agents in Production

Artifacts and related services are usually provided by **production networks** where autonomous enterprises are linked by relatively stable material, information, and financial flows. The members that are cross-linked by information and communication technologies are not only able but also willing to interact with each other, i.e., exchange information about their products, intentions (plans), expectations (forecasts), and status. Agents offer adequate ways for modeling, controlling, and simulating such complex production systems that should be **cooperative** and **responsive** (Váncza et al. 2011). As shown in Fig. 3, the structure of such a network is defined by autonomous production nodes and logistics links (a). Each node has its own internal decision mechanism, typically on various levels of aggregation, from long-term sales and operations planning via medium-term production planning down to production scheduling and control (b). Finally, each node has its own execution mechanism where plans are realized on the shop floor (c). These three main levels – network, enterprise, and shop floor – define a layered decision scheme where targets are set hierarchically, in a top-down way. On all levels, responsiveness requires timely decisions, though the timescales are consistent with the appropriate level. It is also essential to respond to both new or altered demands (coming usually from an upper level) and changes and disruptions (feedback from a lower level). At all levels, the system has to be robust in face of various disturbances coming from the environment.

Industrial Applications

There are some barriers for the industrial take-up of agent technologies, such as scalability,



Agent Theory, Fig. 3 Multilevel enterprise model (After Váncza et al. 2011)

inherent complexity, safety, risk of inconsistent global operation, the appearance of inevitable conflicts between self-interested entities, and the extra burden of communication. Until recently, the industrial acceptance of MAS in manufacturing has not kept up with expectations, partly because of the above issues and partly because of the difficulties in their stepwise integration with existing legacy systems. Against all the above difficulties, there is a consensus concerning the application areas of highest potential:

- Where neither access to information nor decision rights can be centralized. This is the case in managing supply networks, including transportation and material handling.
- In complex operations management – such as resource allocation, planning, and scheduling – where the problems can be decomposed along distinct goals and performance objectives.
- In industrial monitoring and control where robustness and fast reconfigurability are essential requirements in a distributed setting.

All in all, agents hold the promise for resolving compelling challenges that are rooted in generic conflicts between competition and cooperation, local autonomy and global behavior, design and emergence, planning and reactivity, and uncertainty and a plethora of information (Váncza et al. 2011). Developments in various agent technologies are still extremely dynamic, innovative, and ramifying. At the same time, there is also a strong commitment to convergence with current industrial software technologies. The evolution of multi-agent systems and manufacturing will proceed hand in hand: the former can receive real challenges from the latter, which, in turn, will have more and more benefits in applying agent technologies.

Cross-References

▶ Artificial Intelligence
▶ Autonomous Production Control
▶ Distributed Manufacturing
▶ Holonic Manufacturing Systems
▶ Open Architecture

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Agent-Based Computing

▶ Agent Theory

Aluminum Cast Alloys

▶ Machinability of Aluminum and Magnesium Alloys

Aluminum Wrought Alloys

▶ Machinability of Aluminum and Magnesium Alloys

Angular Contact Ball Bearing

▶ Bearing

Anisotropy

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Synonyms

Orthotropy

Definition

As the opposite of isotropy, the term anisotropy defines the dependency between the material response for a defined loading level and the loading direction.

Theory and Application

Introduction

One can distinguish between a "general" anisotropic and an orthotropic material behavior. In sheet metal forming one can usually assume orthotropic behavior in the elastic-plastic behavior due to the production process of the semi-finished part by means of rolling. For bulk metal forming, the anisotropic behavior comes more and more into picture and is also limited to the orthotropic type. The elastic region is assumed as isotropic usually because the influence on the forming process itself is negligible. Because anisotropic behavior plays a very important role in sheet metal forming, in the following only this type of semifinished products and the related application in theory and application will be mentioned.

As mentioned before, anisotropic behavior in sheets is an orthotropic system, sometimes also called as "orthorhombic" symmetrical system. That means along the symmetry planes equality between left and right is taken place (Lange 1990).

In general, an orthotropic material can be identified by the attribute of uncoupling between normal and shear components – the coupling coefficients of **C** (e.g., C_{14}) in the following equation are equal to zero.

$$\sigma = C \cdot \varepsilon \tag{1}$$

To describe this kind of anisotropic material behavior precisely, the yield surface is needed. For quite simple but well-known and established yield surfaces, the so-called r-values are used to describe this behavior. The r-value (normal anisotropy) is defined by the ratio of width to thickness strain (measured as true strains). The index indicates the angle between drawing and rolling direction of the material. Usually, the r-values are determined in 0°, 45°, and 90°.

The mean normal anisotropy is defined as

$$\bar{r} = \tfrac{1}{4}(r_0 + 2r_{45} + r_{90}) \tag{2}$$

and can be used to evaluate the formability in deep drawing. The next defined indicator is the planar anisotropy Δr as

$$\Delta r = (\bar{r} - r_{45}) \tag{3}$$

regarding the tendency to earing during deep drawing.

Because most of modern high-strength materials show great differences in the biaxial stress point, a biaxial anisotropic coefficient is defined as

$$r_b = \frac{\varepsilon_r}{\varepsilon_t} \tag{4}$$

whereby an biaxial stress is applied to a specimen, e.g., in the hydraulic bulge test or the layer compression test. The indices r and t indicate the rolling and transversal direction, respectively.

These more practical motivated values are used for a rough classification for sheet metal forming processes. In order to simulate these processes, suitable yield criterions and definitions of yield surfaces are needed, which are described next.

Yield Criteria

The accuracy of the simulation results is given mainly by the accuracy of the material model. In the last years, the scientific research is oriented in developing of new material models able to describe the material behavior (mainly the anisotropic one) as accurate as possible (Barlat et al. 2004; Banabic 2010; Banabic et al. 2010). The computer simulation of the sheet metal forming processes needs a quantitative description of the plastic anisotropy by the yield locus.

For the case of an isotropic metallic material, the well-known von Mises yield criterion is often sufficient to describe yielding. This is, however, not true for anisotropic materials, especially aluminium sheet metals. In order to take into account anisotropy, the classical yield criterion proposed by von Mises should be modified by introducing additional parameters. A simple approximation for the case of planar anisotropy is given by the quadratic criterion of (Hill 1948):

$$\sigma_1^2 - \frac{2r_0}{1+r_0}\sigma_1\sigma_2 + \frac{r_0(1+r_{90})}{r_{90}(1+r_0)}\sigma_2^2 = \sigma_0^2 \tag{5}$$

Anisotropy, Table 1 The yield criteria developed for description of the anisotropic plastic behavior

Author, Year	σ_0	σ_{15}	σ_{30}	σ_{45}	σ_{60}	σ_{75}	σ_{90}	σ_b	r_0	r_{15}	r_{30}	r_{45}	r_{60}	r_{75}	r_{90}	r_b
Hill's Family																
Hill 1948	x								x			x			x	
Hill 1979	x							x	x							
Hill 1990	x			x			x	x				x				
Hill 1993	x						x	x	x						x	
Lin, Ding 1996	x						x	x	x			x			x	
Hu 2005	x			x			x	x	x			x			x	
Leacock 2006	x			x			x	x	x			x			x	
Hershey's Family																
Hosford 1979	x								x						x	
Barlat 1989	x								x						x	
Barlat 1991	x			x			x	x								
Karafillis, Boyce 1993	x			x			x		x			x			x	
Barlat 1997	x			x			x	x	x			x			x	
BBC 2000	x			x			x	x	x			x			x	
Barlat 2000	x			x			x	x	x			x			x	
Bron, Besson 2003	x			x			x	x	x			x			x	x
Barlat 2004	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
BBC 2003 (2005)	x			x			x	x	x			x			x	x
BBC 2008	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Druckers Family																
Cazacu-Barlat 2001	x		x	x		x	x	x	x		x	x		x	x	
Cazacu-Barlat 2003	x		x	x		x	x	x	x		x	x		x	x	
C – P - B 2006	x		x	x		x	x	x	x		x	x		x	x	
Polynomial criteria																
Gotoh 1977	x		x	x		x	x	x	x		x	x		x	x	x
Comsa 2007	x			x			x	x	x			x			x	x
Soare 2007 (Poly 4, 6, 8)	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Other criteria																
Vegter 1995	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	

where r_0 and r_{90} are anisotropy coefficients at 0° and 90° from the rolling direction, and σ_0 is the uniaxial yield stress in the rolling direction.

In case of a material exhibiting only normal anisotropy, $(r_0 = r_{90} = r)$ imposes that $\sigma_0 = \sigma_{90}$ and Eq. 5 take the following form:

$$\sigma_1^2 - \frac{2r}{1+r}\sigma_1\sigma_2 + \sigma_2^2 = \sigma_u^2 \tag{6}$$

where r is the normal anisotropy coefficient, and σ_u is the uniaxial in-plane yield stress.

Barlat successfully extended the Hosford's 1979 criterion to capture the influence of the shear stress and proposed the following yield function:

$$f = a|k_1 + k_2|^M + a|k_1 - k_2|^M + (2-a)|2k_2|^M = 2\sigma_e^M \tag{7}$$

where

$$k_1 = \frac{\sigma_x + h\sigma_y}{2}; \quad k_2 = \left[\left(\frac{\sigma_x - h\sigma_y}{2}\right)^2 + p^2\tau_{xy}^1\right]^{\frac{1}{2}} \tag{8}$$

while a, h, p, and M are material parameters (Barlat and Lian 1989).

In Table 1 the main yield criteria developed for description of the anisotropic plastic behavior

Anisotropy, Table 2 The main commercial FE software and the anisotropic yield criteria implemented in them

Software	Hill'48	Hill'90	Barlat'91	Barlat 2000	Vegter	BBC 2005
ABAQUS	x	x	x	x	x	x
AUTOFORM	x	x				x
LS-DYNA	x	x	x	x	x	x
MARC	x	x				
PAM STAMP	x	x	x		x	
STAM PACK	x	x				

are presented (see more details in Banabic 2010). The mechanical parameters used for the identification of the models are also presented.

Barlat 2000, Vegter, and BBC 2005 models have been implemented in the last decade in the main FE commercial codes (see Table 2).

In the next paragraphs the most used models implemented in the FE commercial codes are shortly described.

BBC 2005 Yield Criteria

Banabic et al. (2005) proposed a new expression of the plane stress potential. An improvement of this criterion has been implemented in the finite element commercial code AUTOFORM version 4.1 (Banabic and Sester 2012). The equivalent stress is defined by the following formula:

$$[a(\Lambda+\Gamma)^{2k}+a(\Lambda-\Gamma)^{2k}+b(\Lambda-\Psi)^{2k}=\bar{\sigma} \tag{9}$$

where $k\in\Im^{\geq 1}$ and $a,b>0$ are material parameters, while Γ, Λ and Ψ are functions depending on the planar components of the stress tensor:

$$\begin{aligned}\Gamma &= L\sigma_{11}+M\sigma_{22}\\ \Lambda &= \sqrt{(N\sigma_{11}-P\sigma_{22})^2+\sigma_{12}\sigma_{21}}\\ \Psi &= \sqrt{(Q\sigma_{11}-R\sigma_{22})^2+\sigma_{12}\sigma_{21}}\end{aligned} \tag{10}$$

The identification procedure calculates the parameters a, b, L, M, N, P, Q, and R by forcing the constitutive equations associated to the yield criterion to reproduce the following experimental data: stresses and anisotropy coefficients in tension along three directions, the balanced biaxial flow stress, and biaxial anisotropy coefficient.

Barlat 2000 Yield Criterion

The expressions of the two isotropic yield functions considered in (Barlat et al. 2003) are:

$$\begin{aligned}\phi'(\mathbf{s}) &= |s_1-s_2|^m,\\ \phi''(\mathbf{s}) &= |2s_2+s_1|^m+|2s_1+s_2|^m\end{aligned} \tag{11}$$

leading to the resulting anisotropic yield function

$$\phi=\phi'(\mathbf{X}')+\phi''(\mathbf{X}'')=2\bar{\sigma}^m \tag{12}$$

where m is the Hosford's exponent, $\mathbf{s}$ is the deviatoric stress tensor, and $\mathbf{X}$ the linearly transformed stress tensor.

Using the following linear transformation on stresses:

$$\begin{aligned}\mathbf{X}' &= \mathbf{C}'s=\mathbf{C}'T\sigma=\mathbf{L}'\sigma,\\ \mathbf{X}'' &= \mathbf{C}''s=\mathbf{C}''T\sigma=\mathbf{L}''\sigma\end{aligned} \tag{13}$$

where and (or and) represent the linear transformations and $\mathbf{T}$ a matrix relating the deviatoric to the Cauchy stresses:

$$\begin{bmatrix}X'_{xx}\\ X'_{yy}\\ X'_{xy}\end{bmatrix}=\begin{bmatrix}C'_{11} & C'_{12} & 0\\ C'_{21} & C'_{22} & 0\\ 0 & 0 & C'_{66}\end{bmatrix}\begin{bmatrix}s_{xx}\\ s_{yy}\\ s_{xy}\end{bmatrix}$$
$$\mathbf{T}=\begin{bmatrix}2/3 & -1/3 & 0\\ -1/3 & 2/3 & 0\\ 0 & 0 & 1\end{bmatrix} \tag{14}$$

A similar expression with double prime defines $\mathbf{C}''$. A plane stress state can be described by the two principal values of and

$$X_{1,2} = \frac{1}{2}\left(X_{xx} + X_{yy} \pm \sqrt{\left(X_{xx} - X_{yy}\right)^2 + 4X_{xy}^2}\right) \quad (15)$$

with the appropriate indices (prime and double prime) for each stress.

Vegter Yield Criterion

Vegter and Boogaard van den (2006) proposed the representation of the yield function with the help of Bézier's interpolation using directly the test results (pure shear point, uniaxial point, plain strain point, and equi-biaxial point).

The analytical expression of the criterion is

$$\begin{pmatrix}\sigma_1\\ \sigma_2\end{pmatrix} = (1-\lambda)^2\begin{pmatrix}\sigma_1\\ \sigma_2\end{pmatrix}_i^r + 2\lambda(1-\lambda) \times \begin{pmatrix}\sigma_1\\ \sigma_2\end{pmatrix}_i^h + \lambda^2\begin{pmatrix}\sigma_1\\ \sigma_2\end{pmatrix}_{i+1}^r \quad (16)$$

for s_e and angle j where

$$\begin{pmatrix}\sigma_1\\ \sigma_2\end{pmatrix}_{i+1}^r = \sum_{j=0}^{m\cos}\begin{pmatrix}a_l^j\\ a_2^j\end{pmatrix}_i^r \cos(2j\varphi) \quad (17)$$

is a trigonometric expansion associated to the reference point;

$$R(\varphi) = \sum_{j=0}^{m\cos} b^j \cos(2j\varphi) \quad (18)$$

is cosine interpolation of the function $R(\varphi)$; φ is the angle between the principal directions and the orthotropic axes; λ is a parameter of the Bézier function; r is a superscript denoting the reference point; h is a superscript denoting the breaking point; $\begin{pmatrix}a_1^j\\ a_2^j\end{pmatrix}_i^r$ are parameters of the trigonometric interpolation to be determined at the reference points; b^j are parameters of the trigonometric interpolation of the R-function.

Subsequent Yield Surfaces Due to Kinematic Hardening

The above described yield criteria are equal to the description of the yield surfaces as long as isotropic hardening is assumed. Usually, all technical materials have some additional kinematic behavior, which means a translation of the yield surface in the stress space.

Figure 1 shows the effect of this so-called backstress-tensor $\boldsymbol{\alpha}$ as the translation of the surface center. Variants (a) and (b) can be seen as theoretical extremes because only case (c) is observed in the experiment. The general yield condition for such kind of material behavior looks like

$$(s-\alpha)(s-\alpha) = 2K_0^2 \quad (19)$$

where $\boldsymbol{s}$ and $\boldsymbol{a}$ are the stress tensor and the backstress-tensor, respectively.

Usually, the material starts with a kinematic behavior. With increasing strain level, the kinematic behavior saturates and isotropic hardening is taken place. The "problem" now is to describe the behavior of $\boldsymbol{\alpha}$ as a function of the strain and strain-rate level. Several models are available but only the models from Armstrong and Frederick (Armstrong and Frederick 1966) and the Yoshida model (Yoshida and Uemori 2002) are described in the following because of their popularity in the last decades.

Armstrong-Frederick Model (A-F Model)

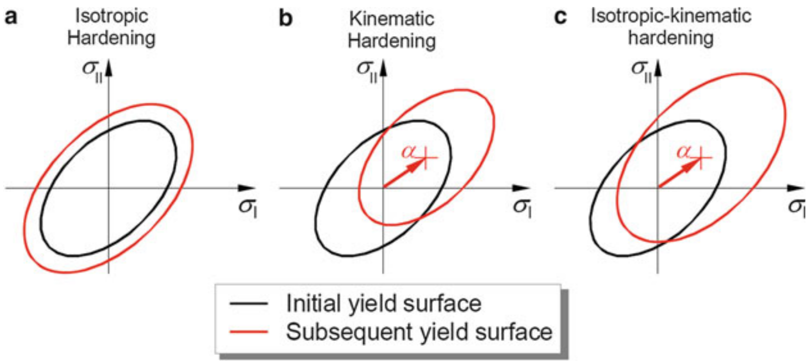
As mentioned above, the calculation for a given strain increment is the key to calculate the backstress-tensor $\boldsymbol{\alpha}$ for a defined strain path because

$$\alpha = \int_0^{t_\varepsilon} \dot{\alpha} \cdot dt \quad (20)$$

For the A-F model, the backstress-tensor rate is given by

$$\dot{\alpha}_{ij} = \phi\left(\dot{\varepsilon}_{p,ij} - \frac{\alpha_{i,j}}{p*} \cdot \dot{\varepsilon}*\right) \quad (21)$$

where $p*$ is a scalar function of the plastic strain path, e.g., the arc length of the strain path is the plastic strain rate and is a scalar.



Anisotropy, Fig. 1 Comparison of hardening type-yield surfaces in stress space

Unfortunately, this type of model has the drawback that re-yielding and hardening stagnation after re-yielding cannot be fitted to "modern" steels like dual phase or complex phase steels, which gives the motivation for the short introduction of the following second model.

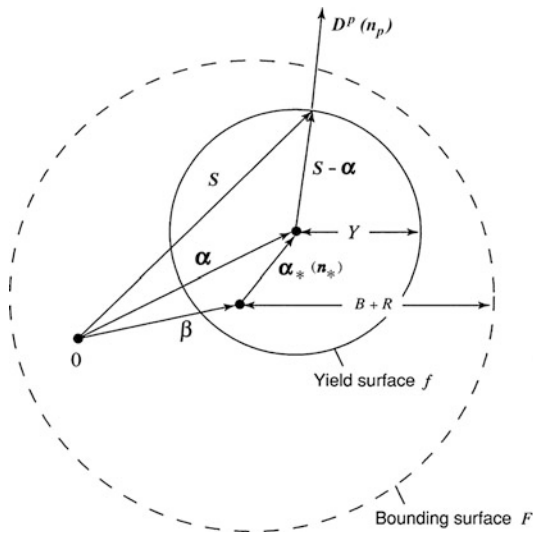
Yoshida-Uemori Model (Y-U Model)

Contrary to the previous mentioned A-F model, the Y-U model uses the assumption of an existing yield surface f inside a bounding surface F (compare Fig. 2) with the basic equations

$$\begin{aligned} f &= \frac{3}{2}(s-\alpha)(s-\alpha) - Y^2 = 0 \\ F &= \frac{3}{2}(s-\beta)(s-\beta) - (B+R)^2 = 0 \end{aligned} \quad (22)$$

Here, $\boldsymbol{s}$ means the stress tensor, $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$ are the backstress-tensors of the yield surface f and the bounding surface F, respectively. Y is the radius of the yield surface; B and R are the initial size of the isotropic hardening.

The kinematic hardening of the yield surface describes the transient Bauschinger deformation characterized by early re-yielding and the subsequent rapid change of hardening rate. The isotropic hardening of the bounding surface represents the global hardening. In order to describe such deformation characteristics under stress reversals, the kinematic hardening and non-isotropic hardening region during stress reversals are assumed for the bounding surface (Yoshida and Uemori 2002).

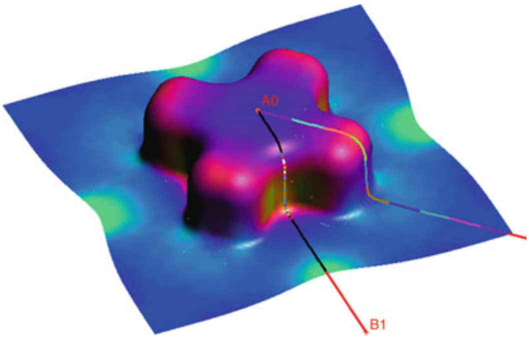


Anisotropy, Fig. 2 Schematic illustration of the two-surface model (Yoshida and Uemori 2002)

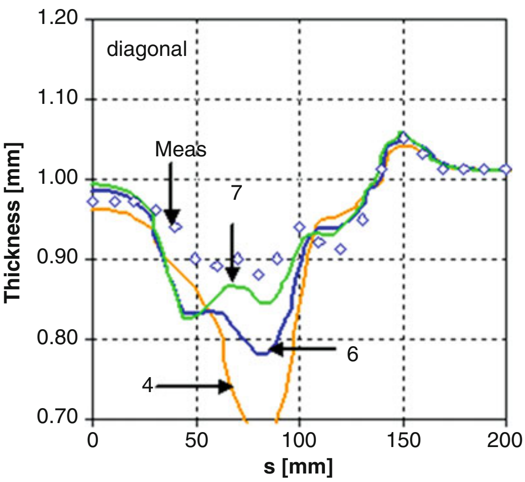
Influence of the Yield Criteria in Numerical Simulation onto Simulation Results

The forming simulation results of a cross geometry are very sensitive to the chosen material model. This is demonstrated for a cross geometry made of an AC121-T4 sheet material (Fig. 3).

The thickness measurements are compared with AutoForm 4.1 simulations using the Barlat and Lian 1989 (using 4 mechanical parameters as BBC2005-4), the BBC2005-6, and the BBC2005-7 models (see Fig. 4). The BBC2005-7 simulation matches the thickness measurements rather well, especially in the meridian cut.



Anisotropy, Fig. 3 Punch geometry



Anisotropy, Fig. 4 Measured and calculated thickness for Ac124-T4 (*diagonal section*). Yield functions: *4* Barlat 1989, *6* BBC 2005-6, and *7* BBC 2005-7

Recommendations on the Choice of the Yield Criterion

Accuracy of the prediction both of the yield locus and the uniaxial yield stress and uniaxial coefficient of plastic anisotropy.

The most important factors that must be taken into account when choosing the yield criterion are as follows:

- Computational efficiency and ease of implementation in numerical simulation codes
- Flexibility of the yield criterion
- Degree of generality
- Number of mechanical parameters needed by the identification procedure
- Robustness of the identification procedure
- Experimental difficulties caused by the determination of the mechanical parameters involved in the identification procedure
- User-friendliness of the yield criterion
- Acceptance of the yield criterion in the scientific/industrial community

Cross-References

▶ Deep Drawing
▶ Formability (Damage)

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ANN

▶ Neural Network

Applications

▶ Microwave Radiation

Arrangement

▶ System

Artificial Intelligence

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Synonyms

Computational intelligence

Definitions

Artificial intelligence (AI) is the science and engineering of making intelligent machines, especially intelligent computer programs that exhibit characteristics associated with intelligence in human behavior including among other faculties of reasoning, learning, goal seeking, problem solving, and adaptability.

AI is not always about simulating or mimicking human intelligence. AI solutions can rely on abilities or methods which cannot be observed in human beings, animals, or communities thereof, for example, the capability to carry out large-scale computations.

Theory and Applications

Introduction

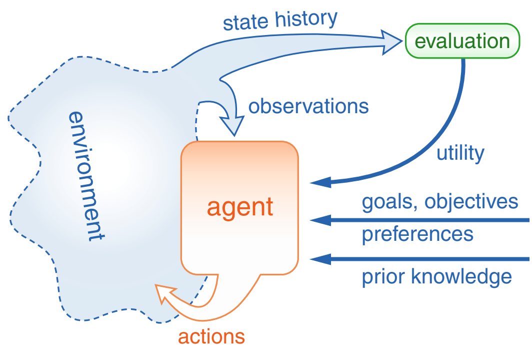
AI is usually originated to Alan Turing, an English mathematician who gave a lecture on AI in 1947. The famous Turing test from 1950 claims that if the machine could successfully pretend to be human to a knowledgeable observer, then it certainly should be considered intelligent.

Like in case of other disciplines, many AI researchers were profoundly optimistic about the future of the new field projecting that intelligent machines can be realized within a relatively short period of time, i.e., a couple decades. “Within a generation . . . the problem of creating ‘artificial intelligence’ will substantially be solved” (Minsky 1967).

Later it became obvious that creating intelligent machines is a far more complex endeavor, and AI has a history of success and failure. In the second part of the 1970s, for example, the undirected exploratory research in AI were cut off (the period is often called as “AI winter”). The first part of the 1980s can be characterized by the commercial success of expert systems and the start of Japan’s fifth-generation computer project. However, the success was questionable, and a second AI winter began.

From the 1990s until now, AI techniques have been successfully applied in different fields like medical and technical diagnosis, character recognition, manufacturing, and logistics, even in computer games. The Deep Blue of IBM was the first system which could beat the reigning world chess champion, Garry Kasparov, in 1997. The success can be contributed to different factors such as the continually increasing computational power of computers (see Moore’s law), more focused application-oriented research, and the combination of different disciplines. However, winning a go party against the best go players is keeping us waiting.

Nowadays we experience that solutions of problems formerly belonging to AI constitute parts of our everyday lives, but newer and newer problems keep on emerging, which call for a further development of the toolbox of AI methods and techniques.



Artificial Intelligence, Fig. 1 The agent and its environment (Monostori et al. 2006)

Some Fundamental Concepts Within AI

Knowledge Representation and Processing

Symbolic approaches are based on the *hypothesis of* symbolic representation – the idea that perception and cognitive processes can be modelled as acquiring, manipulating, associating, and modifying symbolic representations. *Expert systems* represent the earliest and most established type of intelligent systems attempting to embody the "knowledge" of a human expert in a computer program. Knowledge representation in these systems proceeds symbolically in the form of production rules, *frames*, or semantic networks.

A different approach to intelligent systems involves constructing computers with architectures and processing capabilities that mimic the processing characteristics of the nervous system. The technology that attempts to achieve these results is called *neural computing* or artificial neural networks. These *subsymbolic methods* work with *numeric values* and seem to be more appropriate for dealing with perception tasks and perhaps even with tasks that call for combined perception and cognition.

Machine Learning

Machine learning (ML) "denotes changes in the system that is adaptive in the sense that they enable the system to do the same task or tasks drawn from the same population more effectively the next time" (Simon 1983).

Learning processes can be classified by the available feedback, while in:

- Supervised learning the correct response is provided by a teacher.
- Reinforcement learning less feedback is given, since not the proper action, but only an evaluation of the chosen action is given by the teacher.
- Unsupervised learning no evaluation of the action is provided, since no teacher is present.

Various kinds of simple learning methods work with *examples* only, the more powerful learning systems, however, make use of some *background knowledge* of the world too.

Distributed AI, Agents, and Multi-agent Systems

Over the past years significant research efforts have been devoted to the development and use of *Distributed Artificial Intelligence* (*DAI*) techniques (Bond and Gasser 1988). An *agent* is a real or virtual entity able to act on itself and modify surrounding world, generally populated by other agents (Fig. 1). Its behavior is based on its observations, knowledge, and interactions with the world of other agents. An agent has capabilities of perception and maintains at least a partial representation of the environment, can communicate with other agents, has own objectives and an autonomous behavior, and may generate offsprings. A *multi-agent system* (*MAS*) is an artificial system composed of a population of autonomous agents, which cooperate with each other to reach common goals while simultaneously pursuing individual objectives.

Main Branches of AI

Below, the categorization used in (Russel and Norvig 2010) will we followed. Details can be found also in other fundamental textbooks on AI, e.g., in (Nilsson 1998) or (Poole et al. 1998).

Problem Solving

- Search
- Constraint satisfaction

Knowledge and Reasoning

- Logic and logical inference
- Planning
- Knowledge representation

Uncertain Knowledge and Reasoning

- Quantification of uncertainty
- Probabilistic reasoning
- Decision making

Learning

- Learning from examples
- Learning probabilistic models
- Reinforcement learning

Communicating, Perceiving, and Acting

- Natural language processing
- Perception
- Robotics

AI Applications in Manufacturing

Intelligent Manufacturing Systems (*IMS*) were outlined as the next generation of manufacturing systems that – utilizing the results of AI research – were expected to solve, within certain limits, unprecedented, unforeseen problems on the basis of even incomplete and imprecise information (Hatvany 1983).

While in the above formulation the intelligent character of such systems was emphasized, the *Worldwide IMS Program* initiated in 1992 had a much broader perspective: there the foundation of manufacturing science and technology for the next century was put in the center in order "to mobile international industry, government and research resources to drive the co-operative development and spread of manufacturing technologies and systems in a global environment of change" (Yoshikawa 1992).

Growing complexity is one of the most significant characteristics of today's manufacturing, which is manifested not only in manufacturing systems but also the products to be manufactured, in the processes, and the company structures (Wiendahl and Scholtissek1994). The systems operate in a changing environment rife with uncertainty.

AI – mostly together with other disciplines – offers viable approaches to handling complexity, changes, and uncertainties in manufacturing (Monostori 2003). No wonder that AI techniques found their applications in all the levels of manufacturing from design through planning, production, process modelling, monitoring, inspection, diagnosis, maintenance, assembly, system modelling, control, and integration. One of the first comprehensive mappings of AI tools onto manufacturing systems can be found in (Teti and Kumara 1997).

Mappings between application domains in manufacturing (design; process planning; production modelling, monitoring, and control; inspection, diagnostics, and quality control; production planning and control; robotics and assembly) and properties (uncertainty handling, robustness, representation power, explanation, generalization, discovery) of *machine learning* approaches (symbolic classification, explanation based learning, discovery and analogy, pattern recognition, artificial neural networks, neuro-fuzzy approaches) are given in (Monostori et al. 1996).

Various *agent technologies* were found attractive in all main domains of manufacturing because they offer help in realizing important properties as autonomy, responsiveness, modularity, and openness (Monostori et al. 2006). The further evolution of multi-agent systems and manufacturing will probably proceed hand in hand: the former can receive real challenges from the latter, which, in turn, will have more and more benefits in applying agent technologies, presumably together with well-established or emerging approaches of other disciplines.

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Artificial Neural Network

► Neural Network

Assembling

► Assembly

Assembly

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Synonyms

Assembling; Construction; Fitting; Installation; Mounting; Setting up

Definition

Assembly is defined by Webster http://www.merriam-webster.com as:

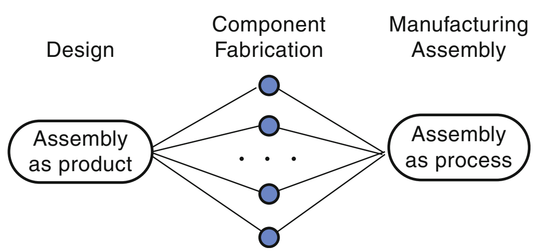
(a) The fitting together of manufactured parts into a complete machine, structure, or unit of a machine
(b) A collection of parts so assembled

Interestingly, the two definitions above are the two branches of assembly research: the process (and systems) of assembling as defined in (a) and product assembly as defined in (b).

Theory and Application

Introduction

Assembly is the beginning and end of product realization. Product development begins with the design of product as an assembly. Questions about design for manufacturing and design for



Assembly, Fig. 1 Role of assembly in product realization

Assembly, Fig. 2 http://www.sciencephoto.com/image/96620/530wm/C0032392-Truck_factory_diesel_engine_assembly-SPL.jpg

Assembly, Fig. 3 Henry Ford assembly line at Highland Park (Henry Ford 1908)

assembly are usually asked and answered during this time. Product realization ends with "assembly" as the capstone process where components and subsystems come together to form the final assembly. The assembly systems play a critical role in product quality, system productivity, and cost. To quote Dan Whitney (2004), "Logistical issues, supply chain management, product architecture, mass customization, management of variety and product family strategies . . . are enabled during assembly design and are implemented on the assembly floor" (Fig. 1).

Assembly Processes

This is the mechanistic view of assembly. Typically, we examine the process steps of putting parts together, including part handling, fixturing, mating, insertion, and welding/joining. These steps can be performed manually, or via automated systems and robots (Fig. 2).

Assembly, Table 1 Productivity gains due to the moving assembly line at Highland Park

Pre-1912	20–30 per day
1913	100 per day
1914	1,000 per day
1915	3,000 per day

Assembly Systems

The first modern version of an assembly system is the moving assembly line introduced by Henry Ford in 1913 at Highland Park, Michigan for producing the Model T automobiles. Prior to the introduction of the assembly line, cars were individually crafted by a group of workers in fixed locations. The process was slow and expensive. The moving assembly line where the cars came to the worker who performed the same tasks again and again was able to significantly improve the speed and reduce the cost of assembly (Henry Ford 1908). An important principle that enabled the moving assembly line is "interchangeability," where individual parts made in large volumes but controlled within tolerance can be assembled in a random order to desired specification and performance (Fig. 3) (Table 1).

The assembly systems introduced by Henry Ford were effective for high-volume production of a single product type with dedicated machines and material handling systems. To respond to the changing market and increasing variety desired by the consumers, more flexible assembly systems have been introduced. Such flexible systems use all purpose machines or robots to handle a variety of tasks in a station associated with the multiple product types. In addition, the assembly systems have also taken on more complex, non-serial configurations (Hu et al. 2011).

Cross-References

- ▶ Assembly Automation
- ▶ Assembly Line
- ▶ Design Methodology
- ▶ Handling
- ▶ Manual Assembly
- ▶ Mass Customization
- ▶ Material Flow
- ▶ Product Architecture
- ▶ Product Development
- ▶ Productivity
- ▶ Welding

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Assembly Automation

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Definition

Automation is the conversion of a procedure, a process, or equipment to an automatic operation without intervention by a human operator (CIRP 2004). In the field of assembly, assembly automation describes the conversion of a manual assembly process to an assembly without a human operator. In general, the term describes the process of increasing the number of assembly steps carried out by automatic assembly machines in a plant.

Theory and Application

History

In the early days, the manufacture and assembly of products was carried out by craftsmen. This led to each part fitting its mating part only. Further, the training of new craftsmen was a long and expensive task as they had to be experts in all areas of manufacture and assembly. In 1793, Oliver Evans developed the concept of conveying materials for an automatic flour mill. In 1801, Eli Whitney completed a factory for muskets for the USA, manufacturing all parts on machines. This led to a higher quality of the product and interchangeable parts for assembly. Still, assembly was an expensive process due to being fully manual and therefore labor intensive and expensive (Boothroyd 2005).

Elihu Root divided the assembly process of a Colt six-shooter into basic operations in 1849. The result was a more efficient assembly process and short periods of worker training (Boothroyd 2005).

Frederick Winslow Taylor introduced the concept of the necessary equipment being in best position for the worker (Boothroyd 2005).

Henry Ford implemented work division, assembly line, subassemblies, and pilot plant of assembly in the assembly of the Ford Model T automobile. While the assembly could be decreased, the process was conditioned by labor cost. The process of replacing people by machines started (Boothroyd 2005).

In 1961, the first industrial robot was used in the handling of die castings at an assembly line for General Motors (Boothroyd 2005).

While the market needs were met with a high batch size of standardized products a few years ago, the current assembly and production lines have to be flexible and agile in order to satisfy the requirements of customers. Due to these requirements, optimized manual assembly systems have become an alternative to automated production systems (Feldmann and Junker 2003). Nowadays, around half of companies use some kind of automation of assembly (Butala et al. 2002).

Due to the high investment cost in relation to the required flexibility, an increased interest is found on hybrid assembly systems where manual workplaces can be substituted by machines and vice versa (Bley et al. 2004). A further kind of hybrid systems allows humans and machines to work in the same workplace of the assembly (Krüger et al. 2009). Another trend can be observed regarding the increase of automation in the final steps of assembly (Hu et al. 2011).

A good example of different degrees of automation in assembly is the today's style of car manufacturing (Hu et al. 2011).

Theory

Motivation for Assembly Automation

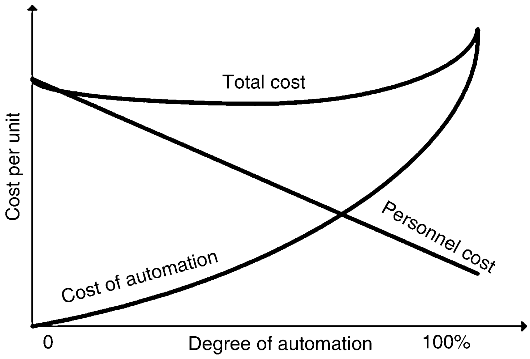
There are several reasons for assembly automation:

- Labor reduction (direct and indirect, e.g., clerks and inspectors) (Riley 1996).
- Reduction of work-in-process inventories (Riley 1996).
- Increase in product quality and quality uniformity leading to a decrease in liability claims and warranty and an increase in competitive advantages (Riley 1996).
- Automatic assembly systems provide an assembly process without breaks and fatigue and a high efficiency for simple assembly tasks (Krüger et al. 2009).
- Increase in overall plant efficiency (Riley 1996).
- Replacement of human labor with insufficient motivation, skills, and education to reach the required unit costs and quality(Riley 1996).
- Removal of operators from hazardous operations (Boothroyd 2005).
- Removal of human operators from monotonous and often stressful high pace work on sequential assembly lines (Hu et al. 2011).
- Automatic assembly forces design for assembly of the product. The improved product design might result in savings higher than the saving due to the automation itself (Boothroyd 2005).

Product Design for Automated Assembly

As the technical and economical feasibility of products depends on the assembly process, an important part of assembly automation is the design for assembly. Hereby the following rules have to be considered (Boothroyd 2005):

- Reduce the number of different parts to a minimum.
- Use of guides and chambers that facilitate assembly.
- Use of self-centralizing screws (cone- and oval-point screws should be used in automatic assembly).
- A sandwich or layer fashion assembly is advantageous for automatic assembly.
- Divide the assembly into subassemblies.
- Design of parts suitable for automatic feeding.
- Use of symmetrical parts.



Assembly Automation, Fig. 1 Cost of unit in dependence of the degree of automation in assembly (according to Ehrlenspiel 2007)

Economic Feasibility

According to Ehrlenspiel (2007) there is an optimal degree of automation where total cost of assembly is the lowest. When degree of automation is below this point, the total cost is dominated by high personnel cost. When the degree of automation is above the optimal point, the total cost is dominated by high cost of automation (see Fig. 1).

Due to the high investment cost of automatic assembly, the following requirements need to be met for the economic implementation of automatic assembly:

- High number of units
- Product design for assembly
- Design of parts for handling
- High quality of parts (Warnecke 1995)

Limitations to Assembly Automation

Automatic assembly has the following technical limitations (Krüger et al. 2009):

- The abilities for handling of complex or limp parts by automatic systems are limited.
- Usually the flexibility of automatic assembly systems, e.g., robots, is limited due to the high programming effort.

The following rules should be considered while choosing the method of assembly:

- Due to the low investment risk with a high level of adaptability and productivity, manual assembly is the best form of assembly in small- and medium-sized companies (Feldmann and Junker 2003).
- For many complex assembly operations, human assembly workers are the most efficient solution (Bley et al. 2004).
- Human workers are the best solution for assembly tasks with a slight variation of products due to being able to adopt to new tasks (Hu et al. 2011).

Cross-References

▶ Assembly
▶ Manual Assembly

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Assembly by Hand

▶ Manual Assembly

Assembly Facility

▶ Assembly Line

Assembly Line

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Synonyms

Assembly facility; Assembly machine; Assembly plant; Assembly system; Production line

Definition

Assembly line is an assembly system in which several workstations are linked together in the sequence of operations required (CIRP 2004).

See Fig. 1.

This is an arrangement of workers, machines, and equipments in which a product passes consecutively from station to station, where specialized and repetitive operations are performed, until a finished product is created much faster than with handcrafting-type methods. It also standardizes operations in order to reduce costs and increase quality.

Theory and Application

History

The assembly line developed by Ford Motor Company between 1908 and 1915 made assembly lines famous in the following decade through the social ramifications of mass production, such as the affordability of the Ford Model T and the introduction of high wages for Ford workers. The principal contributor to the development of the assembly line was Henry Ford (Boothroyd 2005). He described his principles of assembly in the following words:

(a) Place the tools and then the men in the sequence of the operations so that each part shall travel the least distance while in the process of finishing.
(b) Use work slides or some other form of carrier so that when a workman completes his operation, he drops the part always in the same place which must always be the most convenient place to his hand and, if possible, have gravity carry the part to the next workman.
(c) Use sliding assembly lines by which parts to be assembled are delivered at convenient intervals spaced to make it easier to work on them.

These principles were gradually applied in the production of the Ford Model T automobile.

Theory

Types of Assembly Lines

Manual Assembly Line: Assembly systems in which all operations are carried out manually or that consist entirely of manual workstations (CIRP 2004).

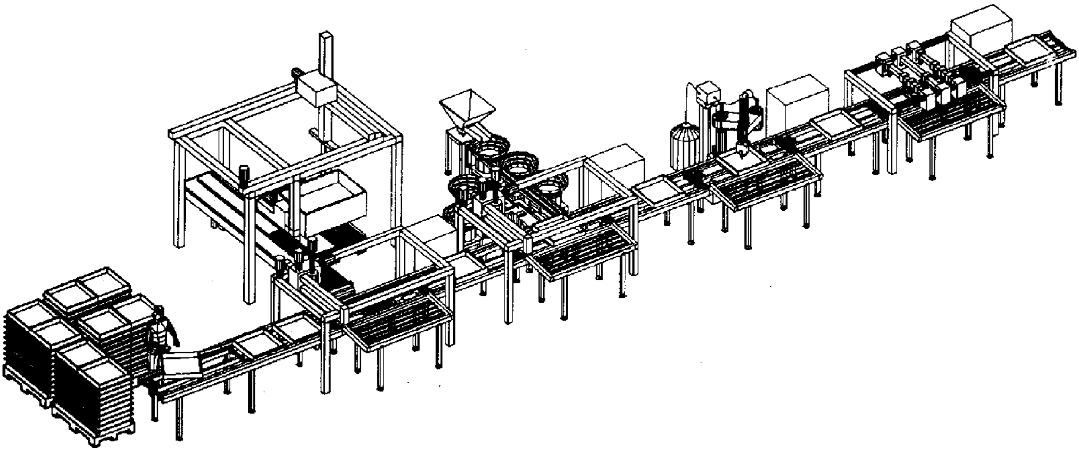
See Fig. 3.

Automated Assembly Line: Assembly systems for the automatic assembly of items using some form of programmable control system (CIRP 2004).

Semiautomated Assembly Line: An assembly system made up from a combination of manual and automatic workstations. See Fig. 5 (CIRP 2004).

The integration of manual workstations in automated assembly systems is necessary if (Lotter 1989):

- On account of their design or sensitivity, the parts cannot be arranged and fed automatically



Assembly Line, Fig. 1 Scheme of a typical semiautomatic assembly line (CIRP 2004)

Assembly Line, Fig. 2 Assembly of the flywheel magneto for the T Model at Ford (Shimokawa 1997)

and these operations must be undertaken manually, e.g., for parts provision.

- Or highly complex assembly operations are involved such that they cannot be economically performed automatically, e.g., for interlocking or highly bendable parts.

Assembly Line Components

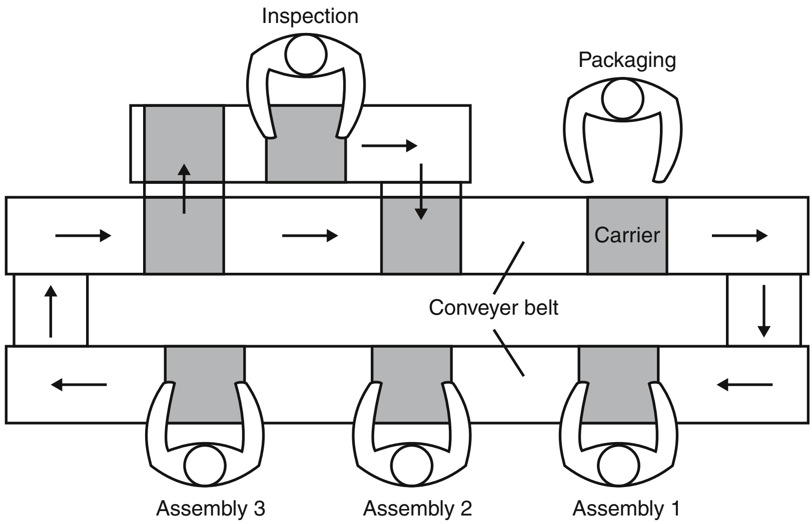
An assembly line may be subdivided into a number of logical or physical components to facilitate the complexity of the design work. The design team usually includes members from several departments; each is responsible for one or more components. The subdivision method and the definitions of components are application dependant (Chow 1990).

- Logical Components

Some logical components, which the assembly line could contain, are:

1. Process design
2. Line balance
3. Test strategy
4. Yield management
5. Material handling
6. Maintenance policy
7. Work-in-process management

Assembly Line, Fig. 3 Manual assembly system (CIRP 2004)



8. Parts procurement
9. Human resource
10. Line size
11. Line layout
12. Information system

- Physical Components

These are, for example, machines, belts, parts feeders, and assembly tables, which are needed to build the assembly line and perform the assembly tasks. Some physical and logical components depend on each other i.e., they should be considered together during the design and analysis of assembly lines.

Choice of Assembly Method (Manual, Automated, or Semiautomated)

Many factors affect the choice of assembly method when considering the manufacture of a new product. The following considerations are generally important:

1. Suitability of product design (Design for assembly) (Boothroyd 2005)
2. Production rate required
3. Availability of labor
4. Market life of the product

When the product has not been designed automated based, manual assembly is probably the only possibility. Similarly, the automation will not be practical unless the anticipated production rate is high. A shortage of the assembly workers will often lead a manufacturer to consider automatic assembly, even though the manual assembly would be cheaper. This situation frequently arises when a rapid increase in demand for a product occurs.

Additionally, the capital investment in automatic machinery must usually be amortized over the market life of the product. Obviously, if the market life of the product is short, automation will be difficult to justify.

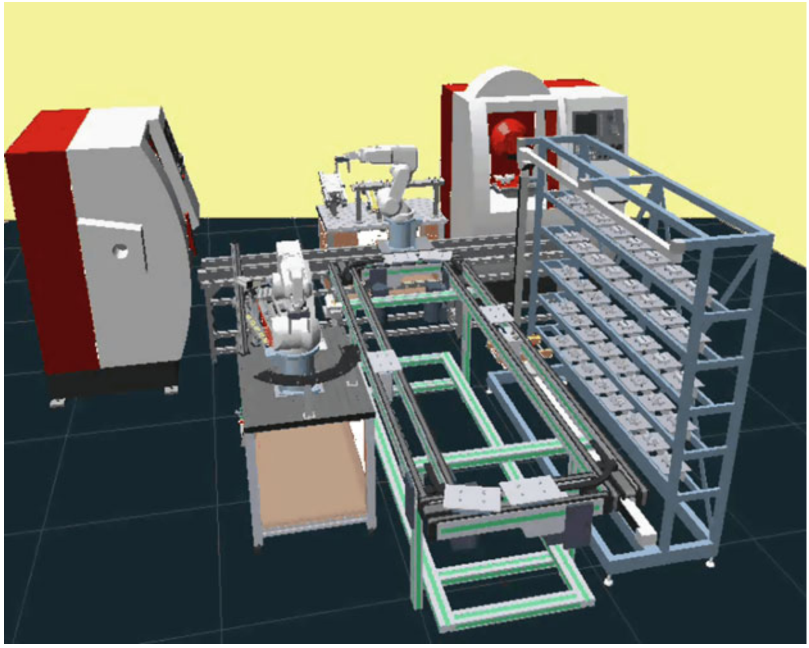
Some advantages of automation applied in appropriate circumstances are:

1. Increased productivity and reduction in costs
2. A more consistent product with higher reliability
3. Removal of operators from hazardous operations
4. The opportunity to reconsider the design of the product

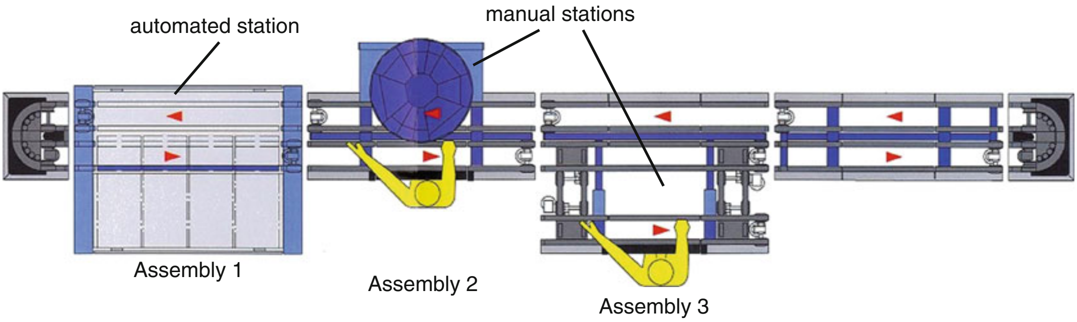
Measures of Effectiveness

There are eight leverages for the enhancement of the line effectiveness (Chow 1990).

Line Capacity It is equal to the maximum expected number of good products that the line can produce per time unit. This number is usually close to but less than the yield capacity of the bottleneck operation.



Assembly Line, Fig. 4 Automated assembly system



Assembly Line, Fig. 5 Semi-automated assembly system (CIRP 2004)

Reliability Reliability of equipment is the proportion of time that the equipment is functioning. For a given period of time, reliability is estimated by taking the ration of period uptime to the total period length. Suppose be the observation time period and be the number of failures observed during the mean time between failures (*MTBF*) and the average downtime per failure (*AVDT*) are, respectively, given by

$$MTBF \approx \frac{total\ uptime}{N} \tag{1}$$

$$AVDT \approx \frac{total\ downtimie}{N} \tag{2}$$

By definition, reliability, r, is the ratio of total uptime during T to T. Therefore, reliability can be characterized by

$$r = \frac{\frac{total\ uptime}{N}}{\frac{total\ uptime\ +\ total\ downtime}{N}} \tag{3}$$

$$\approx \frac{MTBF}{MTBF + AVDT} \tag{4}$$

Production Lead Time This is the total amount of time that a product spends in the line, including waiting and rework.

Work-in-Process The total number of products in the line is a measure of in-process inventory. During a sufficiently long time interval, the average amount of work-in-process is approximately equal to the product of the average lead time and line throughput. This relation is usually a good indication of line performance. An ideal condition is high throughput, short lead time, and low work-in-process.

Workstation Utilization This is the proportion of time that a station is busy doing useful work. For a well-balanced line, all workstations should have approximately the same utilization. If the line is running at full speed, workstation utilization will be close to 1. The average workstation utilization is defined by

$$w = \frac{1}{n}\sum_{i=1}^{n} r_i S_i \qquad (5)$$

where
n = number of workstations
S_i = average process time at workstation i
r_i = throughput at workstation i

Operator Utilization This is similar to workstation utilization, except that operators are more flexible. Sometimes, even for an unbalanced case, workload may be evenly distributed to operators. Operator utilization is a measure for the efficiency of a job assignment policy. The operator utilization is defined by

$$v = \frac{NS}{mT} \qquad (6)$$

where
S = expected total manual process time (including rework, if any)
N = production volume per day
m = number of operators
T = total productive time per day

Line Utilization This is the ratio of production volume to line capacity. Line utilization is given by

$$u = \frac{1}{t_o}\int_0^{t_o} \frac{r(t)}{c(t)}\,dt \qquad (7)$$

where
$c(t)$ = line capacity at t
$r(t)$ = line throughput at t
t_o = product lifetime

Since $0 \le r(t) \le c(t)$, then $0 \le u \le 1$. A line is fully utilized when $u = 1$.

Line Flexibility Line flexibility measures the difference between line capacity and production demand:

$$f = \frac{1}{t_o}\int_0^{t_o} \frac{\min\{c(t), D(t)\}}{\max\{c(t), D(t)\}}\,dt \qquad (8)$$

where $D(t)$ is the demand at t.

The value of f is always between 0 and 1. If $c(t) = D(t)$ for all t, then $f = 1$.

In this case the maximum flexibility is achieved.

Key Applications

Some examples, where the assembly line is deployed, are
- Automobile industry
- Mass production
- Manufacturing of major appliances
- Printed Circuit Board (PCB) production

Cross-References

▶ Assembly
▶ Maintenance

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Assembly Machine

▶ Assembly Line

Assembly Plant

▶ Assembly Line

Assembly Representation

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Definition

A visual representation supplementing the assembly instruction, which shows the structure of the product to be assembled. It shows the chronology and logical sequence of the necessary assembly tasks which leads to the final product.

Theory and Application

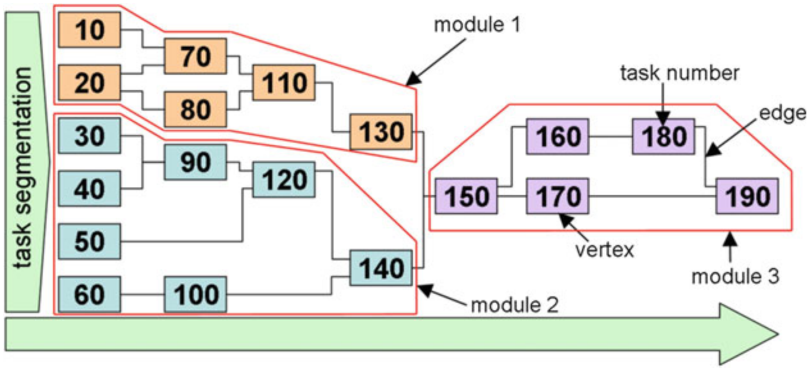
There are several ways to visualize the assembly operations sequence and to describe process and machine parameters as well as instructions for manual assembly. The VDI Guidelines (VDI 2860) specify several basic symbols which represent elementary assembly steps and which can be used to describe complex assembly processes. The illustration of assembly steps in the so-called ▶ virtual reality (VR) and ▶ augmented reality (AR) or by Digital MockUp (DMU) bases upon image sequences of the hierarchically structured ▶ computer-aided design (CAD) data. At this, a fully automatic determination of the assembly order is possible by the analysis of configuration space and the derivation of an optimal strategy or by disassembling a virtual model. Assembly tasks are described in a machine-readable format within the scope of computer-based assembly sequence planning. The known approaches can be divided into three categories:

- Formal linguistic approaches
- Data structure models
- Graph-based approaches

Because of their clearness, the graph-based approaches are considered as the most suitable form of illustration. A lot of different types were developed:

- Assembly precedence graph
- Directed graph/Gozinto graph
- AND/OR graph
- Connected graph/diagram
- Petri nets
- Hierarchical, partially ordered graph
- Assembly boundary condition graph
- Interference graph

In particular the assembly precedence graph is used to plan and illustrate the assembly order as well as to derive programs for computer-controlled machines like robots (Siegert and Bocionek 1996). An ▶ assembly precedence graph is a cycle-free graph that consists of a set of objects where some pairs of the objects are connected by links. The interconnected tasks are represented by mathematical abstractions called vertices, and the link that connects a pair of



Assembly Representation, Fig. 1 Example of an assembly precedence graph

task-nr	task	successors
10	Soldering of connector and cable	200
20	pre-assembly of machine base	70, 80
30	assembly of a traction relief on a M6-screw	90
⋮	⋮	⋮
70	assembly of component 1 on machine base	130
80	assembly of component 2 on machine base	110
⋮	⋮	⋮

task structure

flow structure

Assembly Representation, Fig. 2 Example of a task and flow structure

vertices is called edge. If two tasks are linked, the right task can only be started after the left task has finished. Typically, an assembly precedence graph is depicted in diagrammatic form as a set of boxes for the vertices, joined by lines for the edges. In general numbers inside the boxes represent the dedicated assembly task (Fig. 1) (Bullinger et al. 1993).

For the manual preparation of an assembly precedence graph, tasks are arranged by its earliest feasibility in compliance with predecessors or successors. This can be done by writing the tasks on small cards which can be arranged, e.g., on a flip chart.

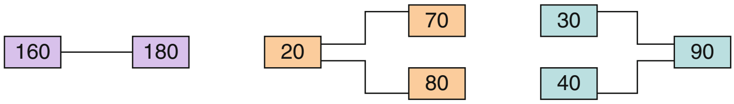
If the assembly precedence graph often needs to be created or changed, the use of computers can be helpful (Ben-Arieh and Kramer 1994; Delchambre 1992). The assembly precedence graph can be created with the following six steps:

– Preparation of product-specific information
– Task structuring of the assembly per module
– Flow structuring of the assembly per module
– Representation of the task and flow structure per module
– Flow structuring of the assembly of the final product
– Representation of the task and flow structure of the final product

The assembly precedence graph can be created based on a task structure (see Fig. 2) (Bullinger et al. 1993).

The task structure can be extended by successors for each task. With this extension it is possible to represent the flow structure. In general the whole assembly structure can be represented by the task and flow structure. As the representation of an assembly structure gets more and more complex, the assembly precedence graph is in most cases easier to understand.

Three essential structure characteristics of an assembly precedence graph can be distinguished.



Assembly Representation, Fig. 3 Three essential structure characteristics of an assembly precedence graph

Referring to Fig. 1 these structures will be explained below (see Fig. 3):

- Basic structure (Fig. 3, left):
  The meaning of the "basic structure" simply is that task 180 can only be executed when task 160 has been finished.
- Splitting into parallel branches (Fig. 3, middle):
  This structural characteristic has the meaning that task 70 and task 80 can only be started when task 20 has been finished. The number of edges leaving a box is not limited to 2.
- Merging of parallel branches (Fig. 3, right):
  This structure means that task 30 and task 40 have to be finished before task 90 can be started. This structure is not limited to only two merging edges. If there are no dependencies between the parts which are needed for task 30 and task 40, these tasks can be executed in parallel. If there are dependencies between the parts, the tasks can only be executed in sequence.

Figure 1 shows an example of a complex assembly precedence graph which is based on the three essential structure characteristics of Fig. 3.

Cross-References

- ▶ Assembly
- ▶ Augmented Reality
- ▶ Computer-Aided Design
- ▶ Product Architecture
- ▶ Virtual Reality

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Assembly System

▶ Assembly Line

Atomic Force Microscopy

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Synonyms

Scanning force microscopy

Definition

Atomic force microscopy, often abbreviated as AFM, is one of the elected techniques for fine surface and geometrical characterization. Atomic force microscopes provide three-dimensional reconstruction of surface topographies with sub-nanometer vertical and lateral resolution, over a range which is typically no larger than a few tens or hundreds of micrometers.

Atomic force microscopes belong to the family of scanning probe microscopy (SPM), a branch of microscopy allowing imaging of surfaces by means of a physical probe scanning the sample surface. SPMs monitor the interaction between the probe and the surface to produce an image or a three-dimensional reconstruction of the surface. SPMs classification is based on the specific physical principles causing the interaction. When such interaction is a force (magnetic, electrostatic, friction, etc.), the scanning probe microscopes are also classified as scanning force microscopes (SFMs). Atomic force microscopy is a specific kind of SFM, where the interaction is an interatomic weak force called the van der Waals force.

Atomic force microscopy was firstly presented in 1986 (Binnig et al. 1986) and commercial systems have been available since 1989. Atomic force microscopy is now a mature measuring technique, implemented not only for research but also in production lines, where high-quality requirements call for high-resolution surface characterization.

Theory and Application

The basic of an atomic force microscope is relatively simple in concept. Its closest predecessor is the stylus profilometer: AFM technology implements sharper probes and takes advantage of lower interaction forces to produce high-resolution topography reconstruction with no damage of the sample surface. Surface topographies are then obtained by mechanically moving the probe in a raster fashion over the specimen and monitoring point by point, line by line the interaction between the probe and the surface as a function of the position.

Technology

An AFM typically includes the following components (Danzebrink et al. 2006): a scanning system, a probe, a probe motion sensor, a controller, a noise isolator, and a computer.

The movement of the tip or sample is performed by an extremely precise positioning device, usually made from piezoelectric ceramics, most often in the form of a tube scanner. Systems based on other actuation principles, such as voice coil, are also available. The scanner is capable of sub-nanometer resolution in x-, y-, and z directions: it is the most fundamental component and the hearth of the microscope.

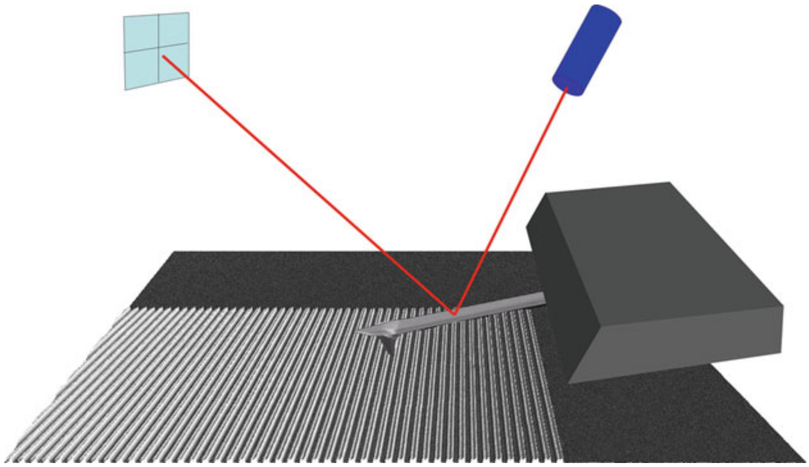
Another AFM key component is the probe. The probe can be moved or stationary: in the first case, it is vertically and horizontally scanned over a standing sample or vertically moved over a sample which is actuated in the horizontal plane; in the second case the actuation system completely acts on the sample allowing it to move under the standing probe. The surface is probed through a sharp tip, located at the free end of a cantilever that is normally 80–400 μm long.

The probe motion sensor controls the force acting between the tip and the surface feedbacking a correction signal for the vertical positioning of the probe relatively to the sample, to keep the force or the distance constant. An optical beam deflection system (optical lever) is often applied for this purpose, ensuring low noise, stability, and versatility. The trend now is to replace the optical lever with "self-sensing" means like, for instance, piezoelectric, piezoresistive, or capacitive.

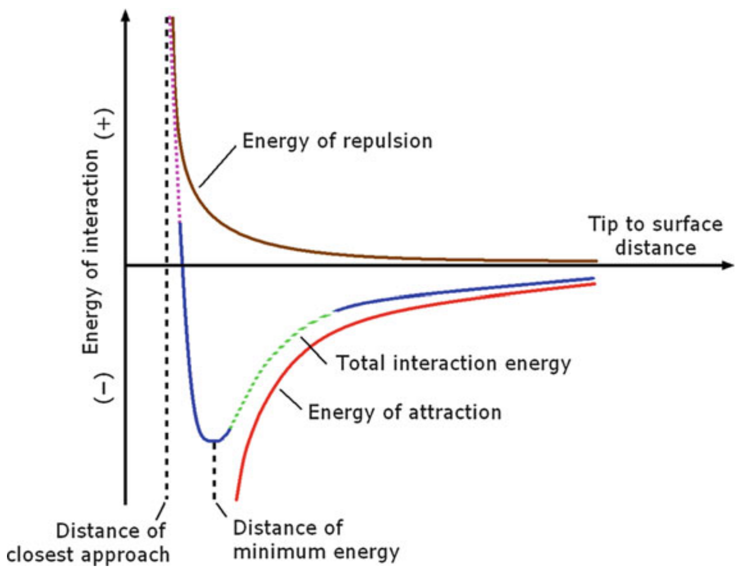
The control unit interfaces the probe motion sensor with the scanning system and a computer. It drives the horizontal and the vertical actuation system supplying proper voltage, corrected with the signal from the probe motion sensor to keep the force or the distance between sample and tip constant.

Additionally active or passive insulation systems are integrated to the instrument in order to reduce external noise (mechanical and acoustic vibrations, electrical and optical noise). A computer and software interface finally is used to drive the system and to process, display, and analyze produced data.

As the tip is scanned over the sample, or the sample is scanned under the tip, forces between the tip and the sample surface cause spatial deflections and oscillations of the cantilever. The key information gathered in AFM comes with measuring those deflections, quantified by means of an optical lever system, coupled with a position-sensitive photodiode (Marinello et al. 2009).



Atomic Force Microscopy, Fig. 1 Optical lever for detection of cantilever deflections



Atomic Force Microscopy, Fig. 2 Total energy of interaction as a function of the distance between the tip and the surface atoms

In Fig. 1, an AFM is represented in contact interaction with the sample surface: during scanning, as z-displacements cause cantilever flexions, the light from the laser is reflected onto the split photodiode.

By measuring the difference signal, changes in the bending of the cantilever can be measured, while an input is given to a servo system that ensures the force or the distance between the sample and the tip to be constant.

Several forces typically contribute to the deflection of an AFM cantilever (Giessibl 2004; Morita et al. 2002). The force most commonly associated with atomic force microscopy is an interatomic weak force called the van der Waals force. The dependence of the energy associated with van der Waals effect upon the distance between the tip and the sample is shown in Fig. 2.

Two distance regimes are put in evidence in Fig. 2:

- The violet-dotted zone, below the distance of minimum energy (typically <1 nm), where the interatomic force between the tip and sample is repulsive
- The green-dotted zone, above the distance of minimum energy (typically about 1–30 nm),

Atomic Force Microscopy, Table 1 Industrial and research applications of AFM technology, by industrial area and level of usage

Product Group	Measurements tasks			Integration level				Applications
	Dimensions	Geometry	Roughness	Applied res.	Industrial res.	Manuf. off-line	Manuf.on-line	
Mechanical parts	↑	↑	↑	■	■	■		Microgears Micromotors Microactuators Sensors (accelerometers,...) MEMS Microphones Microspeakers Hearing aids Surgey devices Implants (stents,...) Particles Microfluidics Micropumps Plasmon resonance sensors Optical switch Micromirrors Lenses Hard disks Magnetic disks Thin Films Micro-injected parts
Microelectronics	↑	↓	↔	■	■	■	■	
Biomedicine and biology	↑	↑	↑	■	■	■		
Chemistry	↑	↓	↑	■	■			
Optics	↓	↑	↑	■	■	■		
Data storage	↑	↓	↑	■	■	■	■	
Polymers and coatings	↓	↑	↑	■	■	■		

↑ = high importance task for the product group; ↔ = medium importance; ↓ = low importance.

where the interatomic force between the tip and sample is attractive

The repulsion regime is used for the so-called contact mode: the tip is scanned across the sample while a feedback loop maintains constant cantilever deflection and force. Other two working modes are commonly used, noncontact and intermittent contact, both operating in the repulsive force region. These are dynamic modes, since the cantilever is oscillated close to its resonance frequency, above the surface. For noncontact AFM the force is measured by comparing the frequency or the amplitude of the cantilever oscillation relative to the driving signal. In the intermittent mode, the oscillation amplitude is significantly higher (~5–30 nm) and the tip rhythmically touches the surface.

Application

Atomic force microscopes are instruments designed primarily for the characterization of surface topographies with a very high spatial resolution. In their first applications, AFMs were used mainly for measuring 3D surface topography and, although they can now be used to measure many other surface properties, that is still their primary application.

Several industrial and research fields benefit from AFM technology. A classification inspired is proposed in Table 1.

This classification encompasses:

- Product groups
- Instrument integration level
- Measurement tasks

"Product groups" run through the technical areas and industries that are applying AFM techniques. As shown in the table, the "integration level" includes applied research studies, with potential industrial interest; studies by industry in research; manufacturing off-line usage, to conclude with the highest level of integration; and the manufacturing online use.

An idea of the type and complexity of the generic measurement tasks to be performed is also given. The classification includes:

- Dimensions, defined as distances between points or surfaces. Example: width, height, or length
- Geometry or form, as defined by the distance between the surface of the object and a predefined reference. Example: flatness or curvature
- Texture and roughness, defined as geometries of surface structures whose dimensions are small compared to the object under investigation. Example: widths, heights, or lengths. Example: bearing analysis, smoothness, or porosity

Typical applications are also reported, not with the aim of exhaustively enumerating all the fields where atomic force microscopy can play an important role, but with the intent of showing the wide and assorted range of technological clusters where AFM brings relevant benefits.

Cross-References

► Scanning Electron Microscope
► Scanning Tunneling Microscope

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Atomistic Modeling

► Molecular Dynamics for Cutting Processes

Augmented Reality

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Definition

Augmented reality is a form of mixed reality where the live view of a real-world environment is enhanced by virtual (interactive) overlay techniques. The original publication that introduced the term was stated as the opposite of VR; use computers to augment objects in the real world instead of using computers to enclose people in an artificial world (Wellner et al. 1993).

The virtuality continuum proposed by Milgram states that augmented reality is just one expression of a mixed reality, which combines real and virtual (Milgram and Kishino 1994).

An augmented reality system has to fulfill three requirements (Azuma 1997):

- Combine real and virtual
- Interactive in real time
- Registered in 3D

Theory and Application

Augmented reality (AR) is a variation on virtual reality (VR). Unlike VR, the user is with AR not completely immersed in a virtual environment. The characteristic of AR is that the user can see the real world, as it is at that moment, with virtual objects projected on or combined with it. AR is used in situations in which the user must be able to relate virtual information to the real situation. Both real and virtual information complement each other; therefore, we can say that AR supplements reality, rather than completely replacing it as VR does. Ideally, it would appear to the user that the virtual and real objects coexisted in the same space (Azuma 1997).

Technology

AR is a combination of hardware and software, the live direct view of a physical real-world environment is generated using multiple sensory inputs such as video (infrared and visible light), location data, movement data, and sound. Software is used to recognize certain objects in the captured data, using the position and orientation of the viewer often in combination with image or tag registration. The output to the user is digital information added as an overlay to the real-life view or often combined with a real-time video of the viewing direction.

Application

The fields of AR can be roughly divided in three areas.

Windowed

A windowed AR application can use normal video screens (varying from mobile phone screens to several meters of diameter) to show a live video stream including the virtual graphic overlay. The overlay is combined with the video stream and is therefore not based on the direction the user is looking, but the direction the camera is facing. This enables multiple users to experience the AR simultaneously. Windowed AR solutions can also make use of half-transparent windows, whereby the user sees the real world through a glass plate on which additional information is projected. With these solutions the viewing direction of the user (single user) is constantly tracked and the virtual overlay is adjusted to that, the real world is hereby not digitally projected.

Immersive

Within an immersive AR application, the user is equipped with a Head-Mounted Device (HMD). This device can be either an optical see-through or video see-through solution. The user sees the world through the HMD, including the virtual graphical overlay. Often the HMD also includes tracking of the position and rotation of the head.

Spatial

In spatial AR environments the computer-generated synthetic information is projected on real objects using digital projectors. The users often do not have direct interaction using a tactile input device and therefore do not have to carry around any technology. The information projected on the real objects is visible for all people with a line of sight and are not user specific.

Cross-References

▶ Computer-Aided Design
▶ Design Methodology
▶ Product Architecture
▶ Product Development
▶ Virtual Reality

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Autonomous Agents

▶ Agent Theory

Autonomous Production Control

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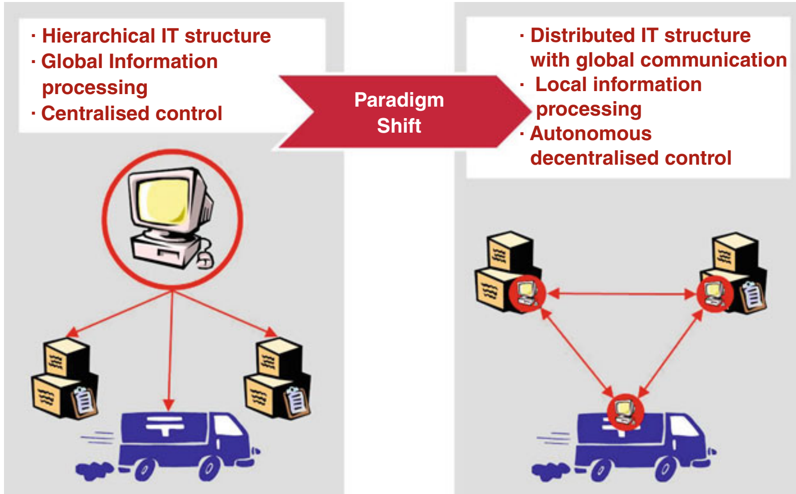
Definition

The dynamic and structural complexity of production and logistics networks makes it



Autonomous Production Control, Fig. 1 From conventional to autonomous control – a paradigm shift (SFB 2012)

very difficult to provide all information necessary for a central planning and control instance. It requires, therefore, adaptive production and logistic processes including autonomous capabilities for the decentralized coordination of autonomous objects in a heterarchical structure. The autonomy of the objects can be realized by novel communication technologies such as Radio Frequency Identification (RFID) and wireless communication networks. These and others permit and require new control strategies and autonomous decentralized control systems for production and logistic processes. In this setting, aspects like flexibility, adaptivity, and reactivity to dynamically changing external influences while maintaining the global goals are of central interest (Fig. 1).

A comprehensive definition of autonomous control is given by Windt and Hülsmann 2007:

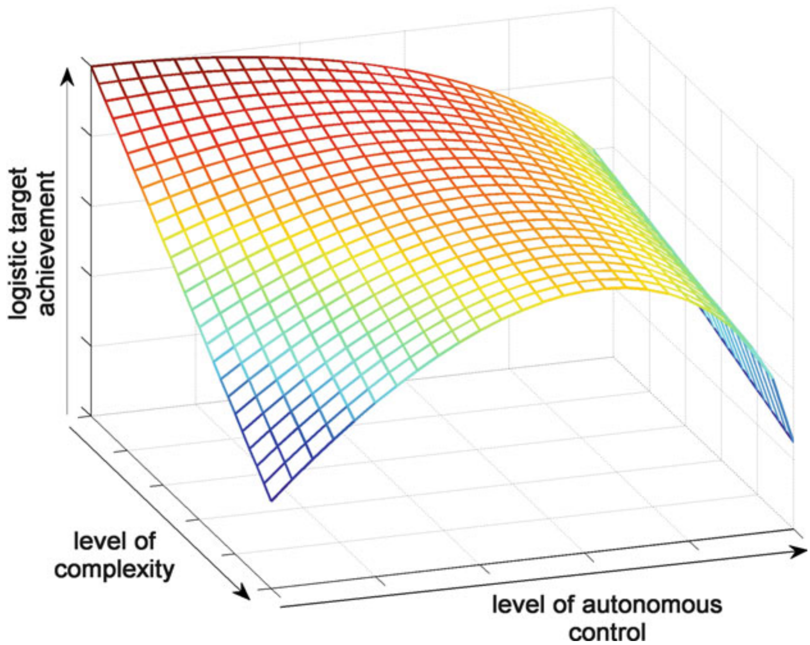
> Autonomous control describes processes of decentralized decision making in heterarchical structures. It presumes interacting elements in non-deterministic systems, which possess the capability and possibility to render decisions independently. The objective of autonomous control is the achievement of increased robustness and positive emergence of the total system due to distributed and flexible coping with dynamics and complexity

Theory and Application

Theoretical Background

The main idea of autonomous cooperating logistic processes is a shift of decision making capabilities from a centralized planning instance to the systems elements. In the context of production systems, elements like production orders or machines are able to make and execute operative decisions on their own. Therefore, these so-called intelligent logistics objects have to exchange, collect, and process relevant information about their local environment. The concept of autonomous control aims at increasing the robustness and the production systems performance under complex and dynamic conditions, due to these local decentralized interactions. Figure 2 illustrates this connection between systems logistic performance, the level of autonomous control, and the level of complexity.

It is assumed that especially in well-defined situations with a low degree of structural and dynamic complexity, centralized planning methods are able to achieve a high degree of logistic performance. However, increasing complexity (e.g., disturbances caused by machine break downs) reduces the logistic performance. In this situation, an increase of the level of autonomy fosters the robustness of the production



Autonomous Production Control, Fig. 2 Correlation between logistic target achievement, level of complexity, and level of autonomous control (Philipp et al. 2007)

system, due to the flexible and distributed decision making. Accordingly, the systems performance can be increased in more complex and dynamic situations. This connection between autonomous control level, complexity level, and logistic target achievement has been investigated by Scholz-Reiter et al. (2009a).

As mentioned above, the communication and the exchange of relevant information between intelligent logistic objects and their decision making process are key aspects of autonomously controlled logistic processes in production systems. The following will describe important enabling technologies, which allow the communication between logistic objects. Subsequently, different autonomous control methods and their decision logics are presented.

Enabling Technologies

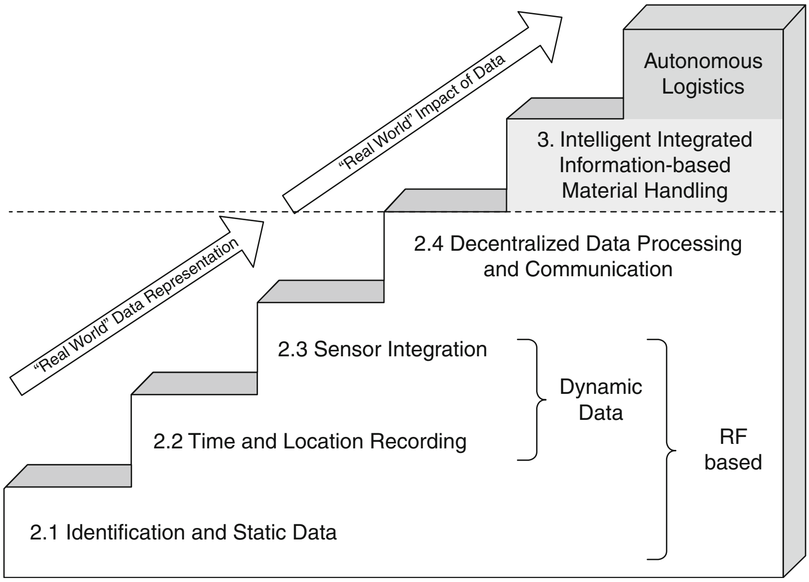
Autonomous control of logistic objects is enabled by new information, communication, and navigation technologies, e.g., RF based. These types of technologies provide sensing, data storage, and data processing abilities as well as the ability to communicate with objects as well as to locate them. RFID is the major enabling technology for autonomous production control. Figure 3 shows the steps from RFID to autonomous logistics.

"Real world" is defined as information physically bound to logistic objects. On RFID tags, identification and static data can be stored. The recording of time and location is also possible with RFID technology and is supported by others, e.g., GPS and Galileo systems. RF-based sensors for temperature and humidity is another field of interest when using RFID for autonomous control in production and logistics.

RF-based technologies provide the technological basis for autonomous control, time, location, and environment sensing.

Autonomous Control in Production Logistics

For production systems, different autonomous control methods have been developed. All of these methods aim at enabling parts in a production system to decide about possible alternative routes through a production system. Although these methods have the same purpose, they differ in their decision logic and in their



Autonomous Production Control, Fig. 3 Stepping from RFID to autonomous logistics (Scholz-Reiter et al. 2008a)

usage of available information. Scholz-Reiter et al. 2010b suggest a differentiation concerning the information used by the different autonomous control methods. This classification comprises local information methods and information discovery methods. Local information methods use only locally available information of the next processing step (e.g., estimated throughput times, WIP levels of buffers, or estimated due dates). According to Windt and Becker (2009), these methods can be furthermore divided into rational strategies, bounded-rational strategies, and combined forms. The group of rational strategies uses rational measures for deciding between alternative production resources. The so-called queue length estimator method belongs to this group. Parts using this method collect information about the workload of available machines and estimate their own throughput time. The part will choose the machine with the lowest estimated throughput time. Contrarily, bounded-rational strategies do not refer directly to rational measures for the decision making process. They rather aim at influencing the total systems behavior positively by the local decision making process. These methods are mainly inspired by biological self-organizing systems, e.g., ants foraging behavior (Armbruster et al. 2006), foraging behavior of honey bees (Scholz-Reiter et al. 2008b), or the chemotaxis movement behavior of bacteria (Scholz-Reiter et al. 2010a).

Similar to local information methods, the group of information discovery methods facilitates the local autonomous decision making of intelligent logistic objects. However, they differ in their information horizon. A particular methods belonging to this group is the distributed logistics routing protocol (DLRP), which is inspired by wireless communication protocols. It collects information of a production system or network by sending and receiving requests to the machines. On this basis, the decision making process comprises additional information about future system states.

Autonomous Control in Production Networks

These autonomous control methods are not limited to single production systems. Furthermore, they can be applied to more complex systems like production networks. Production networks are characterized by multiple production facilities which are interconnected via transport systems. Production networks focus on integrated planning of geographical dispersed and company spanning processes as well as the planning of usage of common resources

(Wiendahl and Lutz 2002). Accordingly, additional planning task, e.g., the assignment of orders to plants or the coordination of production and transport processes, occur. First approaches have shown that autonomous control methods can be applied to production networks. The implementation of autonomous control methods may help to harmonize the material flow through the production and transport system (Scholz-Reiter et al. 2009b).

Application

Application Scenario "Production Logistics/ Factory of Autonomous Products"

The "Factory of autonomous Products" shows how products route themselves through an assembly scenario. The implemented autonomous control methods enable the products to change their target variant as well as the sequence of the assembling steps during processing. Thus, the products can autonomously react fast and flexible to dynamic environmental influences. Hence, the autonomous products achieve an increased robustness of the total logistics system.

http://www.biba.uni-bremen.de/download/log-dynamics/Factory_of_autonomous_productst.wmv

Application Scenario "Automobile Logistics"

This application illustrates the logistical processes which take place within and between the terminals operated by the automobile logistics service provider. The automobile terminals are equipped for the technical processing, storage, and transhipment of vehicles. For this demonstrator, an appropriate transport network with nodes (processing stations at the terminals) and edges (road network) has been marked out on the testing floor. The transport of automobiles between the terminals is demonstrated here with remote-controlled models of car transporters modeled on freight liners. The intelligence of both the car transporters as well as the vehicles to be transported is realized by means of PDAs with appropriate software.

http://www.biba.uni-bremen.de/download/log-dynamics/AutoLog_EN.wmv

Application Scenario "Intelligent Container"

The application scenario "Intelligent Container" combines a number of new ideas and methods of autonomous control. At the center of this scenario is the model of a reefer. The intelligence of the container is based on hardware components which are coordinated and represented by the implementation of an agent platform into the container's system and that of the transport good. The hardware components that have to interact in this case comprise the following components: (1) an RFID reader, which oversees the loading process, (2) a wireless sensor network, which enables the monitoring of critical freight parameters, (3) a processor unit, which preprocesses the accumulating data, and (4) a communication module, which enables linkage to external data networks. The complete system configures itself during the loading process.

http://www.biba.uni-bremen.de/download/log-dynamics/IC_EN.wmv

Cross-References

▶ Holonic Manufacturing Systems
▶ Manufacturing System

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Axiomatic Design

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Definition

A design framework built upon the two design axioms for good decision-making during the mapping between "what we want (function requirements)," and "how we can achieve them (design parameters)."

Axiomatic Design Terminology

Axioms	Self-evident truth or fundamental truth for which there are no counterexamples or exceptions. An axiom cannot be derived from other laws or principles of nature.
Functional Requirements (FRs)	A minimum set of independent requirements that completely characterize the needs of the product in the functional domain.
Constraints	Bounds on acceptable solutions. Constraints are requirements, which may look like FRs but are not independent.
Design Parameters (DPs)	Key variables in the physical domain that characterize the design that satisfies the specific FRs.
Process Variables (PVs)	Key variables in the process domain that characterizes the process that can generate the specific DPs.

Theory and Application

Introduction

Axiomatic design was developed in the late 1970s by Prof. Nam Suh at MIT offering two design axioms, Independence Axiom and Information Axiom, that provide a framework for the decision-making for a broad range of systems design (Suh et al. 1978a, b).

Design involves interplay between "what" and "how." A good design generates "how" (design parameters) which satisfy "what" at minimum complexity. Axiomatic design (AD) starts with the distinction of design domains ("what" domain and "how" domain) and systematizes the thought process during the mapping between them. The functional requirements (FRs) are defined as the minimum set of independent requirements that characterize the design goals, "what." These FRs are then mapped into the physical domain, where the design parameters (DPs), "how," are chosen to satisfy those FRs.

The AD process can be summarized as shown below.

1. Conceive the top-level FRs.
2. Map FRs to DPs at the same level.
3. The mapping process can be analyzed or evaluated with the two design axioms to ensure a good design decision at each level of mapping.
4. Above steps (1–3) are repeated top to down in a zigzag manner until the physical solution can be conceived from the mapped DPs.
5. If all the FRs reach leaf nodes (where the conceived FR-DP is clear and no further decomposition is necessary), physical integration of them to a feasible solution will lead to the final design solution.

The key concepts of the AD process are concept of domains, top-to-bottom decomposition, zigzag mapping, and the two design axioms.

The Concept of Domains

Many bad designs result in when designers mix "what" and "how" in the same domain. The concept of domains provides an important foundation of axiomatic design by separating "what" and "how" in different domains. The world of design in product engineering is made up of four different design domains: *customer domain*, *functional domain*, *physical domain*, and *process domain*. The *customer domain* is where customer's needs reside. These customer's needs must be mapped into the *functional domain* and translated into a set of functional requirements. To satisfy functional requirements, design parameters are conceived in the *physical domain*. To produce the product specified in the physical domain, adequate processes need to be developed which are characterized by process variables in the *process domain*. Ideal design process involves mapping from the customer domain to the functional domain, physical domain, and process domain and then to the left on level below and to the right iteratively. This has been sought by many designers as a way to achieve concurrent engineering. A designer's customer domain may be someone's process domain as well as the process domain would be the customer domain of someone else. This results in a chain of domains, which can be studied in the form of supply chain management.

The concept of four domains of product design can be applied to the design of other engineering and social systems as shown in Table 1. Design cases have been made in manufacturing quality systems (Oh 2013), materials design (Suh 1982), software systems (Kim et al. 1991), organization and business systems (Suh 2001), and health-care systems (Peck and Kim 2008).

Mapping (Top-Down, Zigzagging)

After defining top-level FRs, matching DPs need to be conceptualized by mapping FRs to the physical domain. By choosing DPs at the top level, the top-level FRs can then be specified in more detail at one level below. This mapping process (from "what" to "how" and from top to bottom) can be repeated until all the FRs reach leaf nodes (where the conceived FR-DP relationship is clear and no further decomposition is necessary). This mapping process is illustrated in Figs. 1 and 2 as a top-to-bottom and zigzagging (repeated left to right) decomposition path.

Design Axioms

In order to ensure a good design decision at each mapping process, two design axioms can be used.

Independence Axiom

The first axiom, the Independence Axiom, requires an uncoupled or at least a decoupled design, which guarantees independent control of the functionality of the product. The FRs must be translated into DPs without affecting other FRs to satisfy the Independence Axiom. That means the set of DPs has to be chosen so that they satisfy the FRs as well as maintain their independence (Suh 1990).

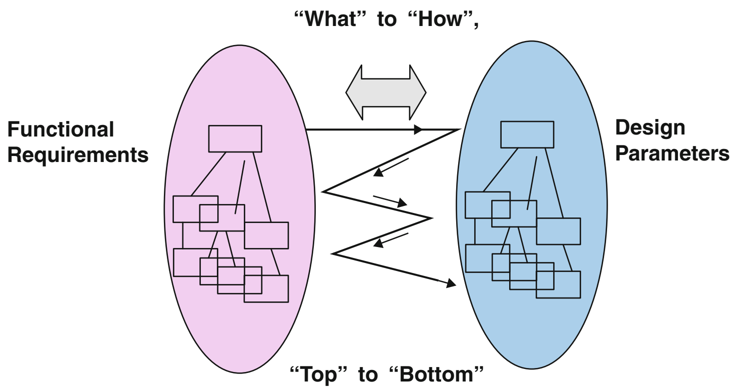
The relationship between FRs and DPs can be written in a design equation as (Suh 1990):

$$\{FR\} = [A]\{DP\} \quad (1)$$

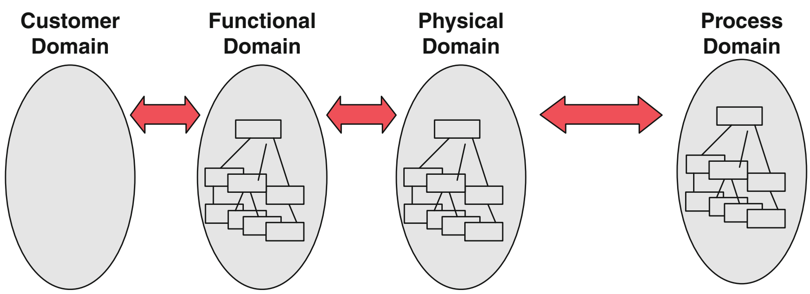
where $[A]$ is the design matrix. For a linear system design, A_{ij} are constants, for a nonlinear design, A_{ij} are functions of the DPs. For an acceptable design in terms of the Independence Axiom, two special cases can occur: the diagonal

Axiomatic Design, Table 1 Four domains of various systems (Suh 2001)

	Customer domain	Functional domain	Physical domain	Process domain
Product design	Customers' desire	Functional requirements	Design parameters	Process variables
Materials	Performance	Properties	Microstructure	Processes
Software	Attributes	Output	Input variables	Subroutines
Organization	Customer satisfaction	Functions of organization	Programs and offices	Resources, people
Business	ROI	Business goals	Business structure	Resources, human, capital



Axiomatic Design, Fig. 1 Mapping between "what" and "how"



Axiomatic Design, Fig. 2 Four domains of the design world in product development

matrix in Eq. 2 which is called "uncoupled design" and the triangular matrix in Eq. 3 which is called "decoupled design." Figure 3 shows an easy-to-understand two-by-two design matrix example on a coupled and uncoupled design of bathroom faucet.

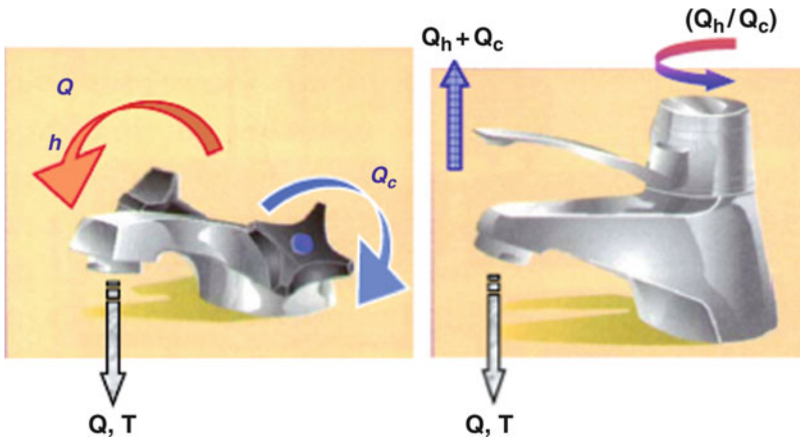
$$[A_{ij}] = \begin{bmatrix} A_{11} & 0 \\ 0 & A_{22} \end{bmatrix} \tag{2}$$

$$[A_{ij}] = \begin{bmatrix} A_{11} & 0 \\ A_{12} & A_{22} \end{bmatrix} \tag{3}$$

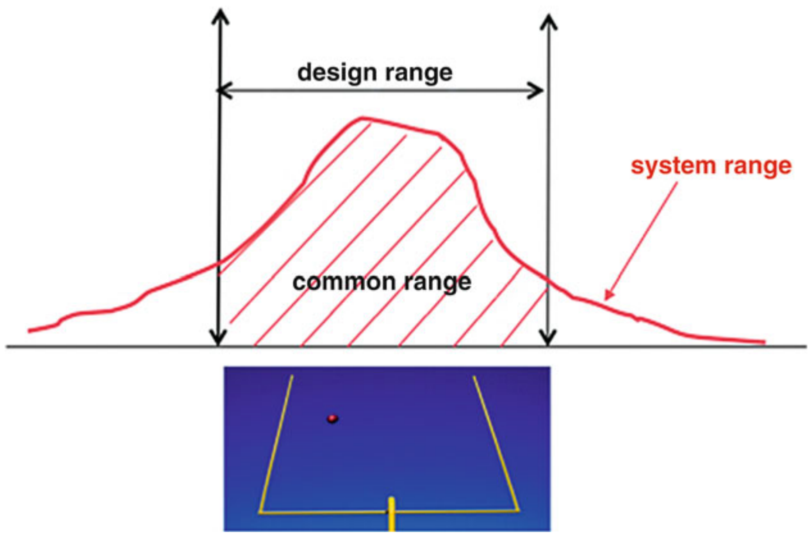
Information Axiom

The second axiom, the Information Axiom, makes it possible to benchmark different design alternatives by comparing their information content. The design, which offers the lowest information content, that is the design with the highest probability of success, will be selected. Information content, I, can be expressed by the following logarithmic function:

$$I = \log_2\left(\frac{1}{p}\right) \tag{4}$$



Axiomatic Design, Fig. 3 Bathroom faucets, getting the right flow rate (FRI) and temperature (FR2): coupled design (*left*) and uncoupled design (*right*)



Axiomatic Design, Fig. 4 Probability of success can be defined by the design range, system range, and common range

$$I = \log_2 \left(\frac{system\_range}{common\_range} \right) \quad (5)$$

where p is the probability of success that the respective FR (with the design range) can be successfully fulfilled by the respective DPs (of the system range). This is similar to the field goal kicker's probability of success, which can be defined as the common area defined by the two poles of the goal extending up infinitely (the design range) and the kicker's accuracy in spraying the ball (the system range). Assuming a uniform distribution of the design range, the probability of success is the ratio of the common range (overlapped area between the design range and system range) over the system range (determined by the kicker's capability) as shown in Fig. 4. If this is close to unity, the probability of success is close to unity and the information content is close to zero from Eq. 4. If the probability of success is very low (close to zero), information content would become infinite, which indicates that the design is very complex and difficult to realize. A desirable design (good design) should have a large common range and thereby have very little information content.

A relative measure of complexity has been derived from axiomatic design (Suh 2005).

Complexity could be defined as a collective outcome when a design does not satisfy the design axioms. The four kinds of complexity can be explained by their causal nature with respect to the design axioms.

– *Time-independent real complexity*: when a design is coupled (Independence Axiom violation)
– *Time-dependent periodic complexity*: when the coupled nature of design is capsulated to prevent the propagation across the system
– *Time-independent imaginary complexity*: when a design is decoupled and not solved in the particular sequence (lack of knowledge)
– *Time-dependent combinatory complexity*: when a design has many states (FRs, DPs), which are not at equilibrium and change as a function of time (nonequilibrium)

Suh suggested functionally periodic systems could have a smaller scale complexity when the complexity is divided and confined in functionally uncoupled spatial/temporal sub-domains. The above speculation about complexity can be applied to very large or small-scale systems design, which has been regarded as extremely complex systems.

Common Design Mistakes Axiomatic Design Can Catch at the Early Stage of Design

Many designers do not recognize that their designs are coupled until they waste time and effort to make their designs working. By simply checking the top 2–3 levels of FRs and DPs, a coupled design can be quickly identified, which will greatly improve the design productivity. Sometimes, this effort can also lead designers to make innovative designs (Suh 2001).

Coupling due to insufficient number of DPs: When the number of DPs is less than that of FRs, a coupled design is resulted always. To avoid this, the number of FRs should be equal to the number of DPs.

More DPs than FRs: This results in a redundant design. To avoid this, the number of FRs should be equal to the number of DPs.

Not recognizing a decoupled design: Although a decoupled design satisfies the Independence Axiom, one must recognize the design is decoupled and then determine (change) the DPs following the right sequence given by the triangular design matrix. Otherwise, the design will be the same as a coupled design.

Functionally coupled design to make a physical integration: Many designers often misunderstand the Independence Axiom by confusing functional independence with physical independence. The physical integration is desirable as long as their functional requirements are independent and uncoupled.

Cross-References

▶ Conceptual Design
▶ Design Methodology
▶ Synthesis

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