E

Early Design

► Conceptual Design

Eco-efficiency

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Synonyms

Environmental cost-effectiveness; Environmental improvement cost; Environmental intensity of production; Environmental productivity

Definition

The World Business Council for Sustainable Development (WBCSD), who has been instrumental in increasing the awareness of the eco-efficiency concept, has defined eco-efficiency as:

Creating more value with less environmental impact

In terms of a definition of the concept eco-efficiency, two equivalent definitions of eco-efficiency are provided: the ratio of value to environmental impact (WBCSD 2000), as in the definition above, and the inversed ratio of environmental impact to value (UN 2003).

Theory and Application

Depending on the application that is studied, the value and impact terms in the eco-efficiency definition can be different entities. The created value can be, e.g., a provided supply, a fulfilled function, a satisfied demand, or an added value. The environmental impact can be some measure of a specific type of impact (e.g., the carbon footprint, the use of water or some other resource, or the emission of toxic compounds to air) or an aggregated measure of environmental impact (see entries on ► Environmental Impact and ► Environmental Impact Assessment).

Eco-efficiency expresses the value creation per caused environmental impact, and when greening industry, the aim is normally to increase the eco-efficiency, i.e., create more value with less impact. WBCSD has proposed the following three operational steps for increasing the eco-efficiency of products:

- Reducing the consumption of resources: this includes minimizing the use of energy, materials, water, and land; enhancing recyclability and product durability; and closing material loops.
- Reducing the impact on nature: this includes minimizing air emissions, water discharges, waste disposal, and the dispersion of toxic

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substances, as well as fostering the sustainable use of renewable resources.

- Increasing product or service value: this means providing more benefits to customers through product functionality, flexibility, and modularity; providing additional services (such as maintenance, upgrading, and exchange services); and focusing on selling the functional needs that customers actually want (WBCSD 2000).

Eco-efficiency studies can be performed at all levels of the industrial system from the process over the plant to the product (life cycle) or conglomerate of industries for an industrial symbiosis system (Duflou et al. 2012). In order to avoid problem shifting when working to increase eco-efficiency of an activity (i.e., to inadvertently create environmental problems elsewhere so the overall eco-efficiency is not increased), it is recommended to apply a life cycle perspective on the activity and to address all relevant environmental impacts of the activity.

In the debate about environmental protection, the focus on increasing eco-efficiency of consumption of products and services (create more value or functionality with less environmental impact) has often turned out to be insufficient. If the increase in population and prosperity and hence in consumption occurs at a faster pace than the increase in eco-efficiency, the combined effect will be an increase in overall environmental impact. Sometimes the increase in (eco-)efficiency in itself promotes an increase in the consumption, e.g., when the more (eco-)efficient product requires less energy and hence becomes more economic in use. This phenomenon which is known as the "rebound effect" has been observed for many consumer activities including energy-using products like private cars where more fuel-efficient cars lead to more driving (Gutowski 2011) and for domestic lighting where the share of the total energy use assigned to lighting purposes has remained close to constant over centuries in spite of more than three orders of magnitude increase in the (eco-) efficiency (Tsao et al. 2010). On this background, some argue for the need for more radical societal changes (Rees 1995), and the concept of absolute decoupling of growth from resource consumption or environmental impact is introduced. Relative decoupling represents more value with less impact, i.e., an increase in eco-efficiency, while absolute decoupling requires a reduced overall level of impact, i.e., taking into account the rebound effect that may occur (UNEP 2011).

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EDM

▶ Electric Discharge Machining

Electric Discharge Machining

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Synonyms

EDM; Electro discharge machining; Spark erosion

Definition

Electric discharge machining (EDM) is defined as the removal of material by electric discharges between two electrodes (workpiece and tool) in a dielectric fluid. The material removal takes place by non-stationary electric discharges (sparks) which are separated from each other both spatially and temporally (CIRP Dictionary 2004).

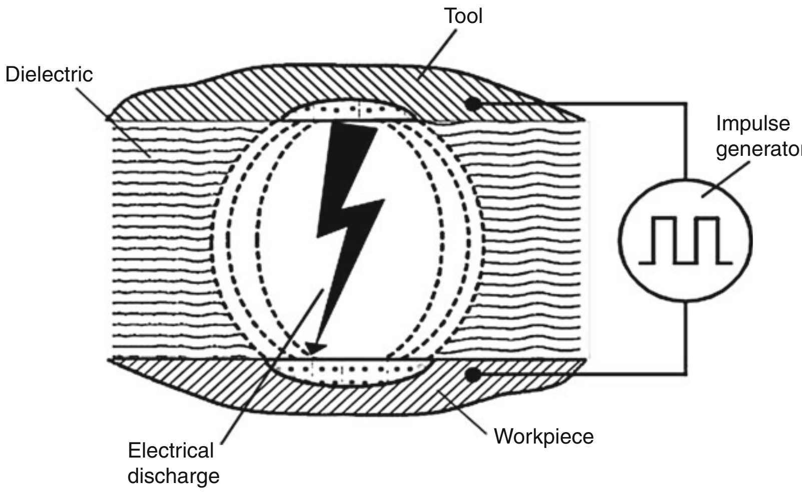
Theory and Application

Theoretical Background and General Principle

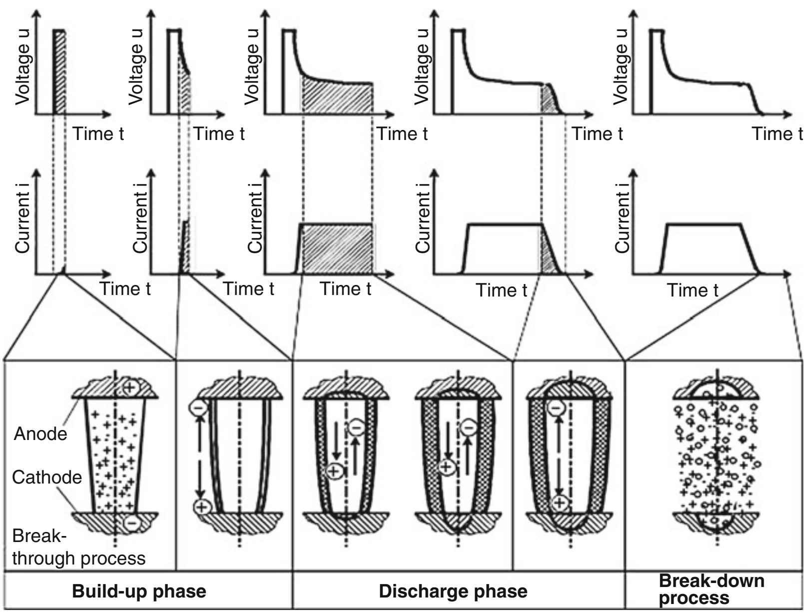
The basic idea of EDM as material removal process is generally traced back to the work of B. R. and N. I. Lazarenko in Moscow who conducted studies on the minimization of wear on electric power contacts. They tested different materials with discharges of defined energy generated by a capacitor. B. R. Lazarenko published the paper "To invert the effect of wear on electric power contacts," in 1943. This idea started the development of EDM, using controlled discharge conditions, for achieving precision machining (Kunieda et al. 2005). As this manufacturing technology is therefore quite young and due to the fact that no conventional mechanical removal principle is involved as in typical long-known cutting processes, EDM is often characterized as an unconventional material removal process.

The concept of EDM incorporates pulsed electric discharges in the "gap" filled with an insulating medium, preferably a dielectric liquid like hydrocarbon oil or deionized water between tool electrode and workpiece (Fig. 1). As the tool electrode shape is copied with an offset equal to the gap size, the liquid should be selected to minimize the gap (10–100 µm) to obtain precise machining. On the other hand a certain gap width is needed to avoid short circuiting, especially when tool electrodes that are sensitive to vibration (like wire electrodes) or deformation are used. The ignition of the discharge is initiated by a high voltage, overcoming the dielectric breakdown strength of the small gap. A channel of plasma (ionized, electrically conductive gas with high temperature) is formed between the electrodes and develops further with discharge duration (Fig. 2). As the material removal per discharge is very small, discharges should occur at high frequencies (range: kHz–MHz). For every pulse, discharge occurs at a single location where the electrode materials are evaporated and/or ejected in the molten phase. As a result, a small crater is generated both on the tool electrode and workpiece surfaces. Removed materials are cooled and resolidified in the dielectric liquid forming several hundreds of spherical debris particles, which are then flushed away from the gap by the dielectric flow (Kunieda et al. 2005).

After the end of the discharge duration, the temperature of the plasma and the electrode surfaces contacting the plasma rapidly drops, resulting in a recombination of ions and electrons and a recovery of the dielectric breakdown strength. To obtain stable conditions in EDM, it is essential for the next pulse discharge to occur at a spot distanced sufficiently far from the previous discharge location. Such a spot may be the place where the gap is the shortest or contaminated with debris particles which may weaken the dielectric breakdown strength of the liquid. Accordingly, the interval time between pulse discharges must be sufficiently long so that the plasma generated by the previous discharge can be deionized and the dielectric breakdown strength around the previous discharge location can be recovered by the time the next pulse



Electric Discharge Machining, Fig. 1 Basic principle of electric discharge machining (Klocke and König 2007)



Electric Discharge Machining, Fig. 2 Time-based evolution of phenomena during the discharge (Klocke and König 2007)

voltage is applied. Otherwise discharges occur at the same location for every pulse, resulting in thermal overheating and a nonuniform erosion of the workpiece (Kunieda et al. 2005).

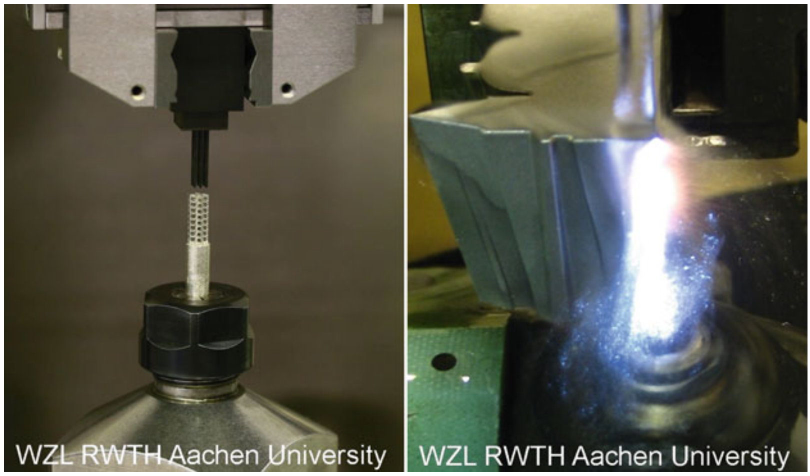
Although a lot of research has been applied to get a better fundamental understanding of the process phenomena, still a lot of scientific questions remain open. Schumacher gives a good summary in the paper "After 60 years of EDM the discharge process remains disputed" (Schumacher 2004).

Process Variants

Today there are three main process variants of EDM established in science and industry – both for macro and micro applications (Fig. 3):

- Sinking-EDM (spark erosion sinking, die sinking, ram sinking).

  Sinking-EDM is defined as EDM process by means of a pre-shaped electrode that is sunk into the workpiece (CIRP Dictionary 2004).
- Wire-EDM (spark erosion cutting, wire erosion).



Electric Discharge Machining, Fig. 3 Sinking-EDM (left) and Wire-EDM (right) as process variants of Electrical Discharge Machining

Wire-EDM is defined as EDM process using an unwinding wire tool electrode that cuts the workpiece according to a given NC path (CIRP Dictionary 2004).

- Drilling-EDM (spark erosion drilling).

  Drilling-EDM is defined as EDM process using one or several cylindrical electrodes for hole making. The feed direction is parallel to the tool axis and the electrodes can rotate (CIRP Dictionary 2004).

Depending on the required geometrical precision and surface quality, different machining strategies are applied ranging from rough machining and main cuts with relatively high discharge energies to finish machining and trim cuts with reduced energies for Sinking-/Drilling-EDM and Wire-EDM, respectively.

In addition further machining axes (A-axis and B-axis) are currently installed on the workpiece table both on Wire- and on Sinking-EDM machine tools which allow more geometrical capabilities by angle indexing as well as fully integrated and controlled additional movements of the workpiece during machining.

Tool Electrode

Common tool electrodes generally incorporate a good electric conductivity and high thermo-physical strength in terms of high melting and evaporation points as well as high heat conductivities and heat capacities in order to reduce the tool wear:

- For Sinking-EDM processes usually copper and graphite are used which incorporate a good formability via cutting operations. Graphite features low relative wear for roughing operations with long discharge duration while copper – and today also more and more fine graphite grades – often reaches slightly better surface qualities during finishing operations with small discharge energies and short discharge durations.
- For Wire-EDM processes brass electrodes are used as standard tools. In addition different coatings based on brass and zinc and surface alterations are applied in order to improve cutting rate, precision and surface finish, as well as wire threading and guidance for conical cutting operations. The tool diameters range from 100 to 330 μm for macro applications. For Wire-EDM in the micro range tungsten and coated steel wires are also quite common. Minimum diameter commercially available is 20 μm.
- For Drilling-EDM different additional electrode materials are used like cemented carbide, tungsten-copper, and silver. The choice depends on the individual process characteristics in terms of low wear, high material removal rate, and good formability. Preferably an

internal electrode flushing could be realized. Maybe a short sentence about internal flushing? Flushing through the electrode?

Dielectric Fluid

The dielectric fluid is a key component for the EDM process and possesses several tasks: At first the tool electrode has to be electrically insulated from the workpiece. During the discharge when the local dielectric strength is exceeded and ionization takes place, a good contraction of the plasma channel has to be maintained. During the pulse interval time after the discharge, a good flushing and cooling effect has to be reached. The two following types of dielectrics are commonly used in EDM:

- CH-based dielectrics (hydrocarbon oil)
- Water-based dielectrics (deionized water)

CH-based dielectrics as best insulators allow the machining at smallest gap sizes. By variation of viscosity the contraction as well as the flushing behavior can be influenced. Generally higher discharge energies and long discharge durations can be used due to higher boiling temperatures (compared to water-based dielectrics). During the machining of low carbon steel, a carbonization of the rim zone could take place.

Water-based dielectrics allow – due to the remaining electric conductivity in the range of 1–10 μS/cm – the dielectric breakdown at bigger gap distances resulting in better flushing conditions. In addition – due to the higher heat capacity and conductivity of water compared to oil – a better cooling can be achieved. Water-based dielectrics are generally more user-friendly but can lead to workpiece corrosion during long machining times.

CH-based dielectrics are commonly used for macro and micro Sinking-EDM as well as micro Wire-EDM processes, while water-based dielectrics are used in macro Wire-EDM operations. Nowadays there are also trends to use CH-based dielectrics in macro Wire-EDM to achieve a corrosion-free superior surface integrity. For Drilling-EDM both dielectrics are in use.

Workpiece Material

In general all electrically conductive materials can be machined by EDM. In this context a minimum electric conductivity in the range of 1–10 S/m was identified for achieving process stable machining conditions. As the material removal rate is generally quite low compared to cutting processes, EDM is usually applied when cutting reaches its limitations, e.g., due to high hardness or difficult-to-cut conditions of the workpiece material or the need for filigree geometries with high aspect ratios. The generally achievable precision for EDM processes is in the μm range and best surface qualities are up to Ra = 0.05 μm. EDM also allows machining of complicated shapes. Since the tool electrode does not need to rotate for material removal as in milling or grinding, holes with sharp corners and irregular contours can be machined without difficulty (Kunieda et al. 2005). The following materials can commonly be machined by EDM:

- Steel and cast iron – independent of heat treatment
- Cemented carbides and cermets
- Electrically conductive ceramics, e.g., SiSiC and Si_3N_4
- Titanium- and nickel-based alloys, e.g., Ti6Al4V or Inconel 718
- Graphite, PCD, metal-bonded cBN, and diamond grinding wheels
- Copper alloys, e.g., AMPCOLOY and tungsten-copper
- Other metals and semiconductors, e.g., aluminum, magnesium, and silicon

Besides the phenomena of melting and evaporation, also other material removal effects like spalling, leaching, oxidation, or electrolysis take place depending on the workpiece material, electric generator settings, and the dielectric medium (Klocke and König 2007).

Application

EDM processes are today applied in a lot of industrial applications ranging from the manufacture of master tools for replication processes like punches and dies to the direct manufacture of small fuel injection holes in series to mass production for the automotive industry. The following list gives a general overview on the important industrial branches and/or key products, respectively, where EDM is applied successfully:

- Mold and die manufacture: punches and high-aspect-ratio geometries on dies and molds
- Tool preparation: PCD machining and conditioning of metal-bonded grinding wheels
- Automotive industry: holes for injection nozzles
- Turbine manufacture: cooling holes and high-aspect-ratio sealing slots
- Special purpose machinery manufacture: high-aspect-ratio holes (up to 1,000:1)
- Fine mechanics: watch parts and form-flexible joints
- Medical engineering: gripper and retina nails
- Prototyping: wheel hubs and lightweight structural components

Traditionally Sinking-EDM has been a general key technology for the die and mold manufacturing industry where a master geometry had to be formed as cavity in hardened steel. Cutting was – due to high tool wear – economically not feasible or even technologically not possible. Due to the significant progress in cutting tool and coating development over the last decades, the application area of Sinking-EDM in mold manufacturing was significantly lost out to HSC cutting processes for low-aspect-ratio geometries. But for high-aspect-ratio geometrical features like rib structures Sinking-EDM is still the most applied technology.

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Electro Discharge Machining

► Electric Discharge Machining

Electrochemical Deposition

► Electroplating

Electrochemical Surface Finishing

► Electroplating

Electroforming

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Synonyms

Electroplating; Electrolytic deposition

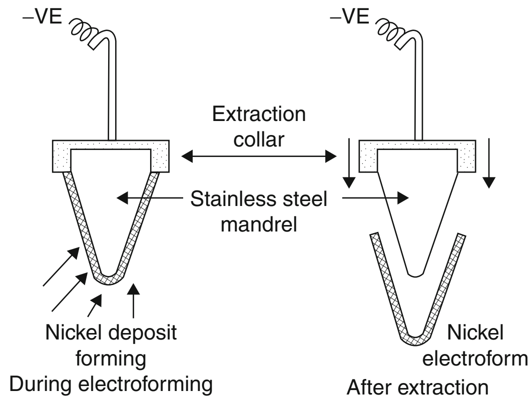
Definition

In electroforming metal is deposited electrolytically upon the cathode-polarized electrode of an electrochemical cell. Unlike electroplating in which the deposited metal has to adhere to the cathode after electrolysis, in electroforming much thicker coatings are applied, the plating is performed on a cathode, and the surface of which bears a nonconducting film so that the deposited metal can be subsequently removed to yield a free-standing artifact or structural component.

Theory and Application

History

Electroforming was discovered by Jacobi in Russia in 1838. During his investigations of galvanic cells, he used an engraved copper printing plate as the cathode with a copper sulfate solution and electrodeposited copper upon it. Although he had difficulty separating the electrodeposit from the engraved printing plate, the deposit had accurately reproduced the details engraved in the original plate. In 1842, Boettger of Germany successfully electroformed an article of nickel. During the latter half of the nineteenth century, electroforming with iron was investigated. Electroforming was promptly applied to the reproduction of art objects, such as sculptures and statues, and to the duplication of engraved plates for the printing of money (Spiro 1968).



Electroforming, Fig. 1 Principles of the electroforming process

Basic Principles of Electroforming

Electroforming is a specialized form of electroplating. The latter process is carried out in an electrolyte solution with a direct current passed between an anode and the part to be plated which is made cathodic. Usually, the anode is metallic nickel or copper which dissolves under the influence of the current passing nickel or copper ions that replace those discharged in the form of metallic nickel or copper on the cathode. The principle is illustrated in Fig. 1.

During electroforming, metallic ions and hydrogen always travel to the cathode (mandrel) and negative ions to the anode. The process follows two fundamental laws discovered by Faraday in the UK:

(i) The mass of a given substance liberated at one electrode is proportional to the total charge which has passed.
(ii) The mass of a given substance liberated at an electrode by unit charge is proportional to the chemical equivalent of that substance.

These two laws can be expressed in the following form: if the mass m is liberated at an electrode when a current I passes for a time t, then

$$m = (A/ZF)It$$

where the quantity A/ZF is the electrochemical equivalent. The electrochemical equivalent is made up of the chemical equivalent of an ion, that is, the atomic weight divided by the valency, divided by Faraday's universal constant. The Faraday is the charge of electricity which liberates 1 g equivalent of an ion in electrolysis.

Theory of Electroforming

Analyses are based on three main equations: Laplace's equation, solutions of which are used to predict the potential between the cathode and anode electrodes of the electroforming cell and particularly at the cathode where metal deposition takes place. From the potential solution so derived, Ohm's law can then be employed to find the current density at the cathode surface and consequently from Faraday's law the rate of electroforming is derived. Theoretical treatments need to take account of current efficiency effects to which are tied the electrolyte properties and periodic reversal of current (McGeough and Rasmussen 1981).

Advantages and Limitations of Electroforming

The electroforming process can replicate fine surface detail with great accuracy. A typical twentieth-century application lay in the manufacture of microgrooved gramophone records. The lateral excursion of the recording needle could not exceed about 0.05 mm. The degree of accuracy provided by electroforming made possible the production of high-quality stereophonic recordings.

The mechanical and physical properties of an electroform can be controlled over a wide range by choice of a suitable metal and by adjusting the plating bath composition and conditions of deposition. With proper choice of a mandrel, parts can be reproduced in quantity with a very high order of dimensional accuracy, which may be of the order of 0.004 μm. All parts produced from the mandrel should be dimensionally identical. There is virtually no limit to the size of object that can be electroformed. Articles have been produced ranging from nickel foil 2.5 μm thick to textile printing screens up to 6 m long. Shapes can be made that are not possible, or very difficult, to manufacture by other methods: for example, seamless radar waveguides with two right angle bends and with the interior being made to close dimensional tolerances and with a high surface finish.

Electroforming is applicable to the production of single pieces or large mass production runs. In the case of electroforming of molds and dies for making plastics, zinc, and glass parts, electroforming can provide tooling with resistance to corrosion, erosion, and abrasion with good heat conductivity and precision parting lines to minimize flashing and with high wear resistance over long production runs. One of the drawbacks of electroforming is associated with the throwing characteristics of an electroplating operation. The deposit produced upon a recessed area of a surface is significantly thinner than on the rest of that surface; thus it may become impossible to produce a deposit in deep recesses. Corner weakness is another disadvantage, restricting the electroforming of components containing recessed areas. The metal deposited into such sharp angles will have a plane of weakness along the line which bisects the angle. If a radius has been provided, the weakness will extend from the center of this radius. If the mold has to support a large stress in such lines of weakness, there is prospect of early failure during its use. The rate of electroforming is very slow, often being measured in days. In addition, the cost of an electroformed article may be relatively high.

Applications

Manufacture of Duplicating Plates

These applications include electrotypes, gramophone record masters, and security printing plates. Nickel electroforming has been used on a large scale in the production of printed plates for bank notes.

Thin-Walled Sections

Foil, sheet, hypodermic needles, fine mesh screens, and seamless tubing are produced by electroforming. For example, electroformed nickel mesh products comprise a large number of current applications. Chief among these are textile printing screens which are used to produce multicolored patterns on textiles, wallpaper, and patterning. The most popular printing screens are seamless electroformed cylinders of nickel consisting of mesh with many fine precise holes. These designs are created on the screen mesh by photoresist techniques which block some of the openings and leave others free. The screens are mounted on rotary textile printing machines on colored feed tubes which are inside and concentric with the large screens. Other meshed products which have been manufactured by electroforming include filters and sieves and electric razor screens.

Parts Difficult to Make by Established Techniques

These include radar waveguides, surface roughness gauges, and fountain pen caps. Electroforming technology is used in the aerospace industries to manufacture lightweight precision parts such as waveguides, antennae, and rocket thrust chambers.

Precision Parts

Tools can be produced by electroforming for plastic injection molding. Electroformed molds have been used successfully for injection molding of thermoplastics, for the die casting of zinc, for the pressing of ceramic materials, and for the pressing of glass.

Micromanufacturing

The combination of lithography, electroforming, and plastic molding termed LIGA was devised by Ehrfeld's group for the mass production, at low cost, of microsized components made from polymers, metals, and alloys. Characteristics include structures of any lateral geometry, dimensions as small as 0.02 μm, aspect ratios greater than 50, and surface roughness of 30 nm. Products such as microturbines and gears can be manufactured as well as microoptics needed for waveguide structures and for compact discs. The manufacture of microelectromechanical systems (MEMS) by micromanufacturing techniques such as electroforming and photoelectroforming is becoming more widespread (McGeough et al. 2001).

Cross-References

▶ Micromachining

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Electrolytic Deposition

▶ Electroforming

Electromagnetic Bearing

▶ Bearing
▶ Magnetic Bearing

Electromagnetically Levitated Spindle

▶ Magnetic Bearing

Electron Beam Cutting

▶ Electron Beam Machining

Electron Beam Drilling

▶ Electron Beam Machining

Electron Beam Machining

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Synonyms

Electron beam cutting; Electron beam drilling; Electron beam processing; Electron beam removing; Electron beam welding

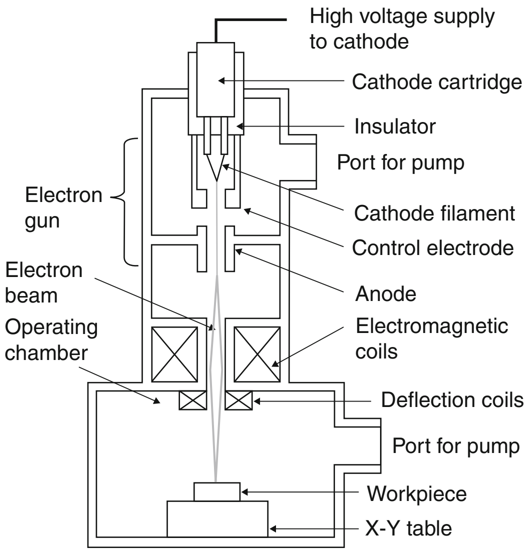
Definition

Electron beam machining (EBM) is a thermal machining process in which high-velocity electrons concentrated into a narrow beam are used for instantly heating, melting, or vaporizing the material. This process is used in many applications, including drilling, cutting, annealing, and welding.

Theory and Application

Introduction

When high-speed electrons in a densely focused beam impact with the workpiece surface, most of the kinetic energy of the electrons is converted into heat energy. This phenomenon has been well understood since the development of electron microscopy when attempts to use the electron beam as a machining tool were made. The first



Electron Beam Machining, Fig. 1 Schematic diagram of electron beam machining equipment

EBM equipment was built in the 1950s. The beam is easily focused and deflected by electromagnetic focusing lenses and deflection lenses. The power density is also easy to control by modifying the acceleration voltage. Therefore, the electron beam enables various type of thermal machining. For this reason, it can be applied to fast and accurate drilling and high-precision welding with a deep fusion zone in the industrial field.

Equipment

Figure 1 shows a schematic diagram of an electron beam machining equipment. It consists of an electron beam gun for the generating electron beam, an electromagnetic coil for focusing the beam, a deflection coil for scanning the beam, a XY table for fixing the workpiece in an operating chamber, and a vacuum system. Figure 2 shows the whole view of a typical electron beam machine (Mitsubishi Electric Corporation index type).

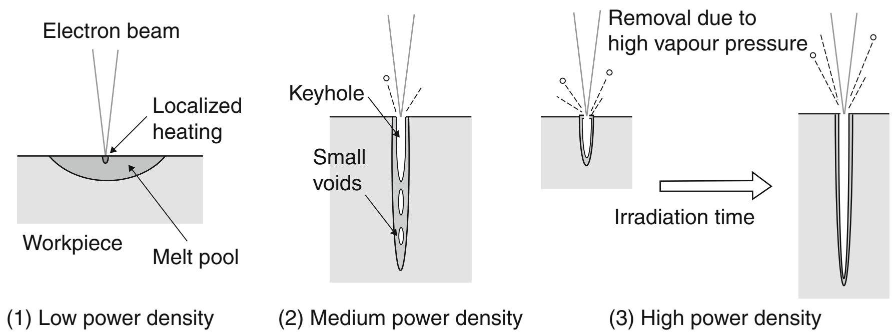
The cathode filament of the electron gun made of tungsten or tantalum is heated to 2,500–2,800 °C resulting in thermal emission of electrons. The electrons are strongly accelerated with high voltage loaded to an anode. The electrons may achieve a velocity as high as 200,000 km/s. Upon leaving the anode, in order to focus the electron beam to the workpiece surface, the beam passes through the electromagnetic coil. The spot size and the focal length are controlled by the current flowing through the coil. The size is usually from several microns to few millimeters, but an electron beam less than 1 μm in diameter can be obtained with relatively small beam currents. The power density on the workpiece surface required to melt or vaporize a metal surface is 10^7–10^{10} W/cm^2. Scanning of the beam is sometimes necessary for drilling an arbitrarily shaped hole. The electromagnetic deflection coil system can be used to position and scan the beam at high speed. The use of the beam scan with the deflection coil is limited to small angle, because beam aberration increases with the deflection angle. For applications requiring larger workpiece, a XY table is commonly translated.

Process

The type of processing requirement determines power density of the electron beam which is utilized. The power density on the workpiece surface is varied with the beam spot size, the acceleration voltage, and the beam current. Low power density with low beam current and small spot size is suitable for the EB exposure for patterning of electronic circuits. On the other hand, high power density with high current and high voltage is needed for the welding or melting/evaporation of metal.

In processes with relatively high power density, the material only within the spot is heated up to a high temperature, and the material is removed by melting and evaporation. The ratio between them depends on the power density and the relationship of evaporation increases with the power density. Figure 3 shows the material removal mechanisms of different power densities of the electron beam. In the case of a low power density, the temperature at the center of beam on the surface is nearly at the melting point of the workpiece material, and the melt pool enlarges due to the heat conduction. When the power density is increased, vaporization of the

Electron Beam Machining, Fig. 2 Electron beam machine



Electron Beam Machining, Fig. 3 Material removal mechanisms of different power densities

material occurs at the center and causes voids and keyholes. The melted material is blown away due to the high pressure associated with the vaporization. In the case of higher power density, the temperature at the spot exceeds the boiling point, and the pressure in the keyhole becomes higher than the surface tension of the melting pool. Thus, the ideal material removal for the drilling of small and deep holes is achieved, in which the material removal effectively progresses along the depth direction. This situation is realized when the power density is 10^6–10^7 W/cm^2.

Advantages

As compared with other thermal processing methods, such as laser processing, the advantage of electron beam machining arises from the feature of the electron beam itself (Closs and Drew 1978; Mesyats 1998; Schneider 1989). They are as follows:

Small Spot

The beam can be electromagnetically focused to an extremely small spot size. The spot size is usually of the order of microns, and a diameter of nanometer level can be achieved under a sufficiently low current condition. Then, further precise micromachining is possible, compared with a laser beam in which the spot size less than wavelength of the light is principally impossible. Also the focal depth of electron beam is longer.

High-Temperature Heating

In addition to its extremely small spot size, an electron can be accelerated to extremely high velocity with the voltage of the anode. Thus, very high power density can be obtained. Power densities of 10^6–10^7 W/cm^2 can be readily achieved. High power density is very effective in instantly heating a highly localized area.

Deep Penetration

With a high accelerating voltage, electrons penetrate to a specific depth. This interaction volume can be calculated with a high degree of accuracy. In other words, the heat energy is supplied inside the workpiece. Thus, a deep keyhole can be generated easily inside the workpiece, and the material removal effectively progresses along the depth direction pulse by pulse. Consequently deep penetration welding and micro deep hole with extremely high aspect ratio are possible.

High-Speed Beam Control

The charge-to-mass ratio of an electron is high. Therefore, the direction of an electron beam is easy to control by electrostatic and electromagnetic forces. Short pulse oscillation of the electron beam is also possible. Synchronizing of the deflection with the pulse oscillation enables drilling of excessively large number of micro holes with high speed and high accuracy. High-speed scanning of the beam enables fabrication of a very complex shape pattern for exposure masks for photolithographic applications.

Application

Drilling and Cutting

The advantages of electron beam machining, such as deep penetration and high-speed controllability, enable the drilling of a large number of micro holes at extremely high speed (Closs and Drew 1978; Schneider 1989). The drillable workpiece thickness is less than several millimeters at thickest even by repeated pulse irradiations, but extremely high-speed process of about 100,000 holes/s is possible in case for small hole diameter less than 100 µm. Thus, the electron beam drilling is applied to drillings of thousands of simple holes, many holes in difficult-to-drill material, such as cooling holes on the inlet ducts of gas turbine engines, many types of filter and spinner heads for fiber production. The heat conductivity of ceramics is so low that the high temperature needed for material removal is easy to obtain, which makes it possible to drill deep holes into ceramic materials. It has also been applied to drilling holes for drawing dies made of alumina and also diamond.

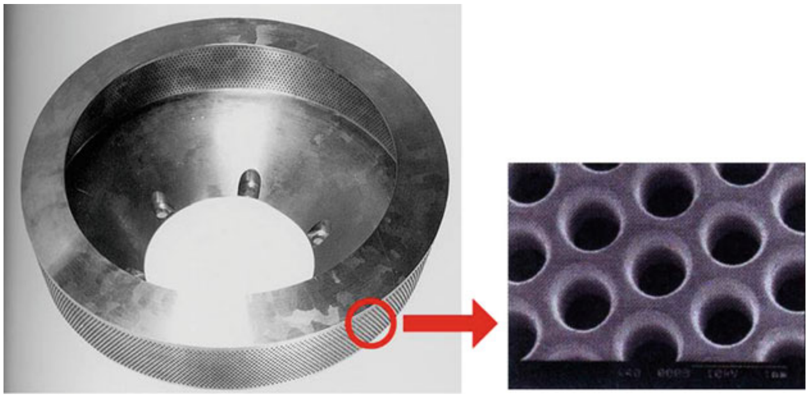
Figure 4 shows a spinner head for glass fiber production. As shown in the figure, so many small holes are made in nickel-based alloy plate by the electron beam drilling. The hole diameter is about 0.6 mm, and the thickness is about 5 mm (furnished by Pacific Special Alloy Castings Co., Ltd.). Figure 5 is a liner strainer made of stainless steel which is used as a filter to remove foreign objects from fruit juice. The diameter is 0.25 mm.

By scanning the beam or moving an XY table, the electron beam can cut metal sheets. The small spot size produces a narrower kerf and a smoother cut surface than other thermal cutting methods.

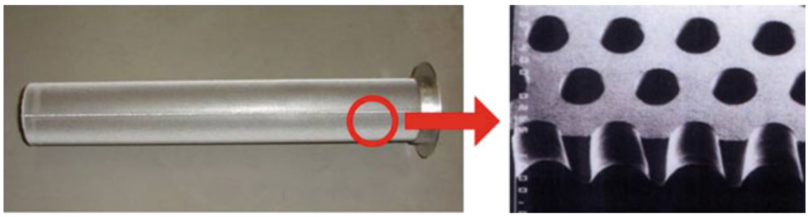
Welding

The electron beam welding is associated with the power density of 10^6–10^7 W/cm^2, which is higher than that observed in the arc welding (Schultz 1994). A deep keyhole is easily generated inside the workpiece and the material removal effectively progresses along the depth direction pulse by pulse. Thus, an extremely narrow and deep fused zone is produced. The aspect ratio is much higher than that in the laser beam welding and the maximum fused thickness is also much thicker, about 200 mm or more. Furthermore, welding strain is small. The welding of chemically active metals and different kinds of metal is also possible.

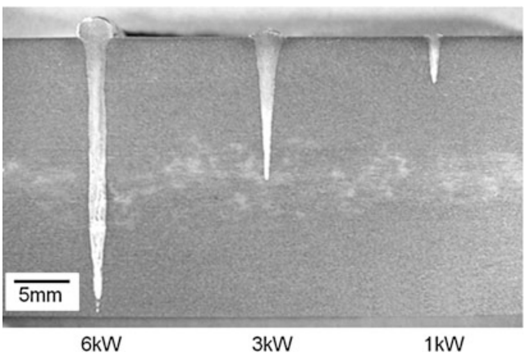
Figure 6 shows the cross section view of welding beads in aluminum by an electron beam welding. The welding bead becomes deeper with the beam power, and it is about 23 mm at 6 kW,



Electron Beam Machining, Fig. 4 Spinner head for glass fiber production



Electron Beam Machining, Fig. 5 Liner strainer



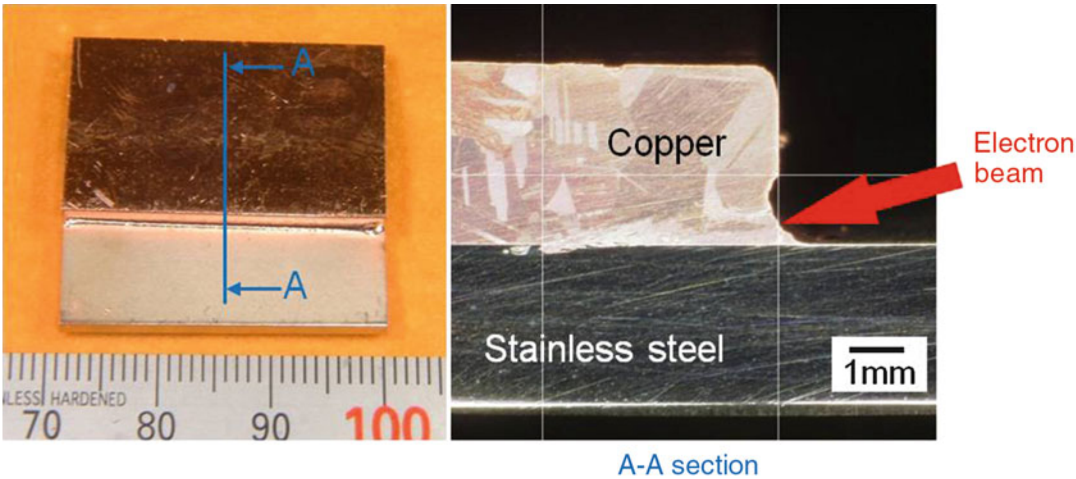
Electron Beam Machining, Fig. 6 Weld beads in electron beam welding of aluminum

while the bead width is only 2 mm. Figure 7 is an example of electron beam welding of different kinds of metal. Copper and stainless steel can be welded by the electron beam welding (furnished by Mitsubishi Electric Corporation).

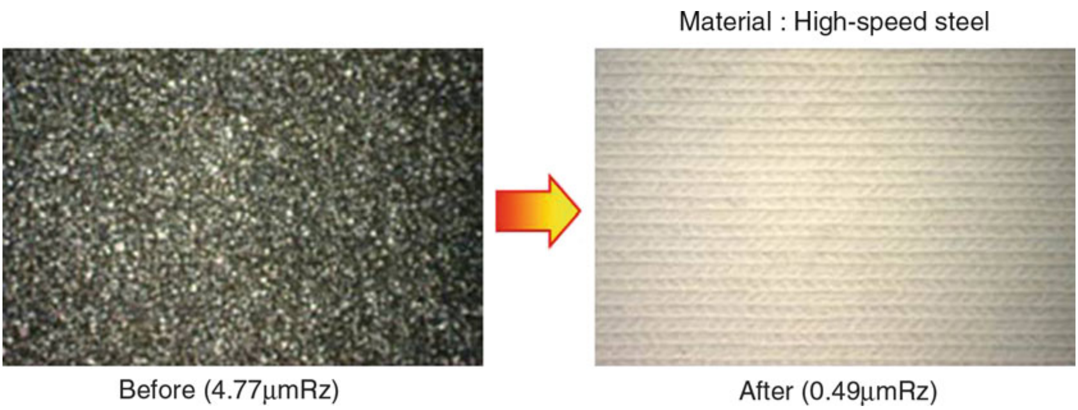
Surface Finishing

A defocused electron beam spot of about several hundred microns in diameter melts metal surface, and rough surface becomes smooth due to the surface tension of small melting pool (Uno et al. 2005). By scanning the spot at high speed, a large area can be finished, in which the surface roughness decreases to less than 1.0 μm Rz under certain conditions. Figure 8 is the optical image of the treated surface by scanning defocused electron beam machine (Mitsubishi Electric Corporation e-Flush).

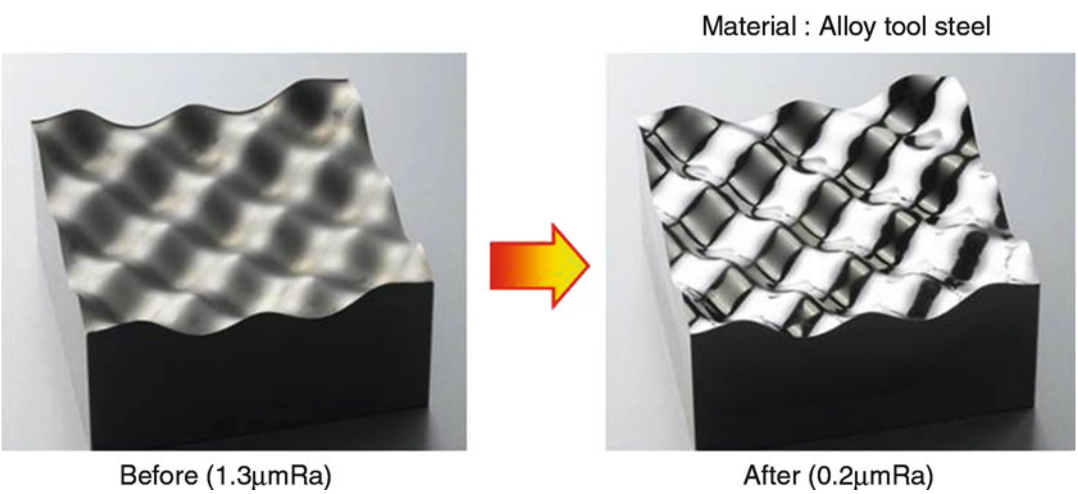
Another method is a surface polishing using large-area electron beam proposed by Nagata Seiki Co., Ltd. and Sodick Co., Ltd. (Sodick PIKA Finish). A high-power-density electron beam can be produced without focusing the beam by using an explosive electron emission phenomenon (Mesyats 1998). Thus, a large-area electron beam with a maximum diameter of 60 mm or more can be used to instantly melt the metal surface. Figure 9 shows the surface finishing of metal mold surface, and the surface roughness can be reduced from 1.0 μm Ra to less than 0.2 μm Ra in a few minutes. In this method, a thin resolidified layer with different structure of base matrix is formed on the surface, which leads to the increase in corrosion resistance and water repellency among other effects. This method is often applied to surface finishing of metal mold surfaces and bio-titanium alloy products.



Electron Beam Machining, Fig. 7 Welding of copper and stainless steel plates



Electron Beam Machining, Fig. 8 Surface finishing by scanning defocused electron beam spot



Electron Beam Machining, Fig. 9 Surface finishing by large-area electron beam irradiation

Cross-References

- ▶ Cutting, Fundamentals
- ▶ Drilling
- ▶ Welding

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Electron Beam Processing

▶ Electron Beam Machining

Electron Beam Removing

▶ Electron Beam Machining

Electron Beam Welding

▶ Electron Beam Machining

Electron Pulse

▶ Pulse

Electroplating

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Synonyms

Electrochemical deposition; Electrochemical surface finishing

Definition

Electroplating means a process by which a layer (metal, alloy, composite, etc.) is produced in an electrolyte under the influence of an electrical current on a conducting substrate. The electrolyte (also called plating bath) contains ions of the material to be plated.

Theory and Application

The theory of electroplating is closely related to the theory of charge transfer processes at electrified interfaces (Bard and Faulkner 2001).

Typical applications comprise the cathodic deposition of metal and alloy layers for surface finishing applications. Many recipes can be found in Schlesinger and Paunovic (2010).

Most electroplating processes are cathodic processes in which the layers are formed by cathodic reduction. As an example let us consider the technically important process of zinc deposition. A simple zinc electroplating bath could be made up by dissolving zinc sulfate in water. The part to be coated with metallic zinc would then be connected to the negative pole of a power supply. The positive pole could be connected to solid zinc bar. Both electrodes would be immersed into the zinc sulfate solution and an electrical current would pass through the solution. At the negative electrode (cathode), the following reaction will occur:

$$Zn^{2+}(aq) + 2e^- \leftarrow Zn(s)$$

And at the positive electrode (anode), we have the following reaction:

$$Zn(s) \rightarrow Zn^{2+}(aq) + 2e^-$$

By using a soluble anode, the concentration of zinc ions in the bath will remain constant. There is usually no need for adjusting the bath composition during the electroplating process. If we had chosen an inert anode (e.g., platinum), the following reaction would occur:

$$2H_2O \rightarrow O_2(g) + 4H^+ + 4e^-$$

In such a process we would have to replenish the zinc ions in the bath by adding zinc sulfate from time to time. Furthermore, we would have to control and adjust the pH of the bath (notice the production of protons at the anode).

Typically electroplated layers are some micrometers thick. The plating rate (i.e., the amount of deposited material per time) is proportional to the electrical current. The total amount of electroplated material is proportional to the passed electrical charge. The ratio of the plated material and the amount calculated from Faradays law is called the current efficiency. If there are no side reactions (e.g., hydrogen evolution), all the passed charge is used to plate out the material from the electrolyte and the current efficiency is 100 %.

Cross-References

▶ Electroforming

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ELID-Grinding

▶ Ultraprecision Grinding

Ellipsometry

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Definition

Collective name for a number of techniques dealing with the measurement and interpretation of the change in the polarization state of a polarized beam of radiation which is reflected from a surface.

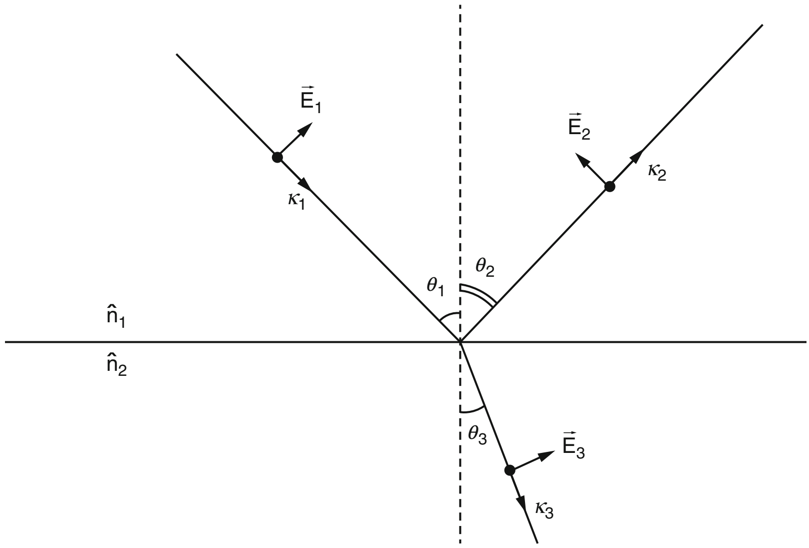
From this change, optical properties of the reflecting surface can be derived.

Theory and Application

Basic Theory for Reflection and Transmission at an Interface and the Basic Ellipsometry Equation

In Fig. 1 the beam trajectories are sketched for a wave incident on a plane interface between two media having a real refractive index n_1 and n_2, respectively. The incoming beam with amplitude E_1 is reflected by the interface, giving a reflected beam with amplitude E_2 and a transmitted beam with amplitude E_3.

The condition that the phase of the three waves must be the same at the interface gives $\Theta_1 = \Theta_2$ and $\sin(\Theta_1)/\sin(\Theta_3) = n_1/n_2$ which is Snell's law. The ratio between the incident amplitude E_1 and the reflected amplitude E_2 will be different between light that is polarized parallel to the interface (p-direction) and the direction perpendicular to this (s-direction, as the arrows in Fig. 1). In general it can be written that



Ellipsometry, Fig. 1 Reflection and refraction at a plane interface

$$r(\lambda, \theta) = \frac{r_p(\lambda, \theta)}{r_s(\lambda, \theta)} = \tan(\psi(\lambda, \theta)) \exp(i\Delta(\lambda, \theta)) \quad (1)$$

where r_p and r_s are the amplitude reflectances for light polarized in the p- and s-directions, respectively. This equation defines the ellipsometric angles Ψ and Δ that can be determined in an ellipsometric measurement as shown below. Equation 1 states that the ratio between the reflectances, and with that the ellipsometric angles Ψ and Δ, will depend on the angle of incidence θ and the wavelength λ for a given interface, whether it consists of a single homogeneous material or is a complicated system consisting of several absorbing and non-absorbing thin films.

Considering Eq. 1, ellipsometry consists of:

1. Measurement of the angles Ψ and Δ

   An instrument that enables the determination of these quantities is called an ellipsometer.

2. Give a physical interpretation to the measured angles Ψ and Δ

   Using the Fresnel coefficients of stratified surfaces, the theoretical angles Ψ and Δ can be calculated of a surface, whether it consists of a single homogeneous material, a birefringent material, or a combination of absorbing and transparent coatings on a surface.

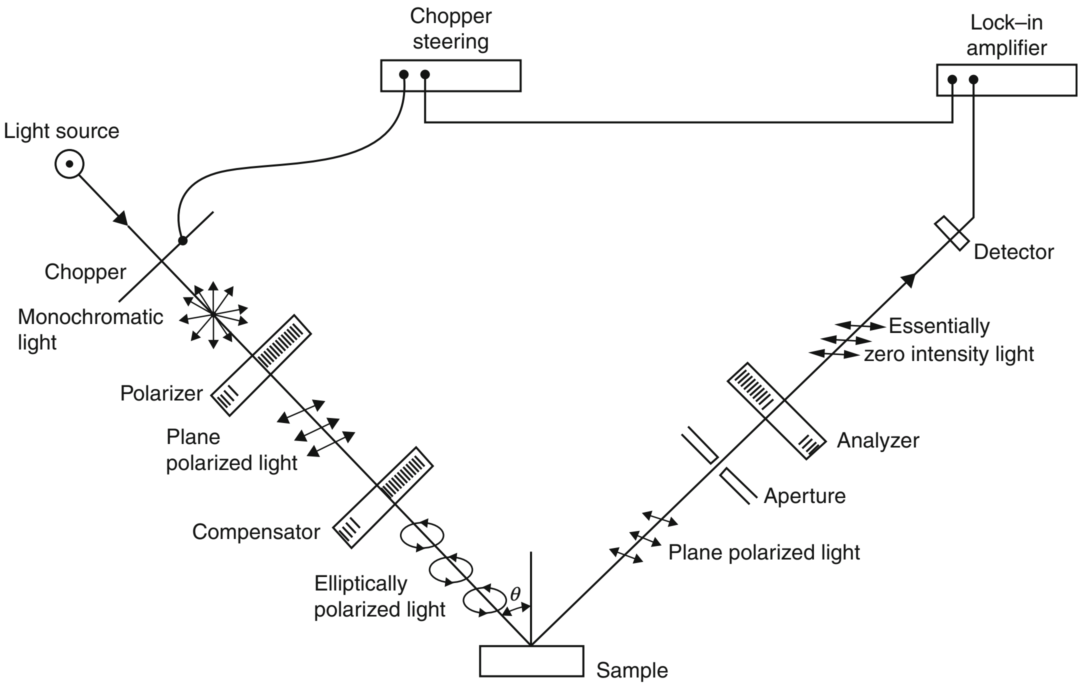
Measurement of Ψ and Δ: The Ellipsometer

Static Null Ellipsometer

An example of an ellipsometer arrangement is given in Fig. 2. It is one of the most elaborate arrangements but it can well illustrate the key points of ellipsometry.

Figure 2 depicts an ellipsometer in the PCSA (polarizer-compensator-sample-analyzer) arrangement. The polarizer, compensator, and analyzer can be rotated around the axis that is defined by the light beam. The polarizer and analyzer are in fact linear polarizers; the compensator is a 1/4-λ plate that is commonly oriented at 45° from the p- and s-direction. The polarizer can be rotated to make a linear polarized beam in any polarizing direction. Together with the compensator this means that polarized light can be made that is either linear polarized in the p- or s- direction, or it is circular or elliptically polarized in any other direction. It is always possible to adjust the ellipticity of this light in such a way that after reflection a linearly polarized beam remains. This light can be extinguished by another polarizer that is called the analyzer.

With every position of the compensator at + or −45°, there are two positions of the polarizer (P) and analyzer (A) where extinction occurs. These four solutions are called the four



Ellipsometry, Fig. 2 Schematic of an ellipsometer according to the PCSA arrangement

Ellipsometry, Table 1 Zone relations for a PCSA null ellipsometer. P is the polarizer angle, C is the compensator angle, and A is the analyzer angle

Zone	Delta	Psi
$C = -\pi/4$	$\Delta_1 = 2P_1 + \pi/2$	$\Psi_1 = A_1$
$C = \pi/4$	$\Delta_2 = -2P_2 - \pi/2$	$\Psi_2 = A_2$
$C = -\pi/4$	$\Delta_3 = 2P_3 - \pi/2$	$\Psi_3 = -A_3$
$C = \pi/4$	$\Delta_4 = -2P_4 + \pi/2$	$\Psi_4 = -A_4$

zones, for which Δ and Ψ are derived according to Table 1:

Table 1 illustrates in the first place that the relationship between the ellipsometer angles and the polarizer position is rather straightforward. In the second place there are four solutions.

The effects of alignment errors in the polarizer, analyzer, and compensator angles, and the retardation of compensator, can be eliminated by taking the average solutions $\Delta = \sum \Delta_i/4$ and $\Psi = \sum \Psi_i/4$, respectively. It is a big advantage of null ellipsometry that this method exists to eliminate most of the systematic alignment errors in this way. The only remaining systematic errors are the rotary scale errors of the P and A position and the error in θ.

The measurement itself consists of rotating the polarizer and analyzer and finding the settings of the polarizer P and analyzer A where light extinction takes place; in practice this is the point where the light intensity has a minimum. This position of P and A is insensitive to intensity fluctuations of the light source and is also insensitive to absolute intensity measurements. By watching the intensity at the detector location this measurement can even be done visually.

Dynamic Ellipsometers

As the null ellipsometer is rather tedious to operate, dynamic ellipsometers have been developed. An example is that the analyzer is rotating continuously in the PCSA configuration. A Fourier analysis of the intensity signal gives the ellipsometer angles Δ and Ψ if the position of the compensator C and polarizer P are known.

Such a signal can be used to monitor a surface. The automatic error compensation of the four-zone null technique must be replaced by a calibration technique for the offsets.

Measurement of a Single Set or Multiple Sets of Ellipsometric Angles Δ and *Ψ*

Determination of Two Parameters

An obvious attractive feature of ellipsometry is that two parameters are obtained in a single measurement. If there is only one perfectly homogeneous surface with a complex refractive index, the real and complex part of the refractive index can be calculated from the two ellipsometric angles. The situation becomes more complicated if the assumed system becomes more complicated: every thin film has a thickness and a complex refractive index, which means three additional parameters.

This means that if useful information is to be obtained from a film-substrate system, there are five parameters: the complex refractive index (n and k) of film (two parameters) and substrate (two parameters) and a film thickness (one parameter). Usually some parameters are known or can be assumed, such as the refractive index of the substrate material and $k = 0$ for a transparent film. In that case the film refractive index and thickness can be obtained from a single ellipsometric measurement. If one needs to determine more parameters, the number of free parameters can be increased by varying the angle and/or the wavelength.

Multiple Angle of Incidence (MAI) Ellipsometry

With MAI ellipsometry measurements at a same specimen at a same location on a specimen are taken, but the angle θ is varied. This gives a new Ψ and Δ value at every angle θ. This means that more parameters can be fitted in a model that contains one or more thin films on a substrate. However, in the model some parameters can be correlated and the dependence on Θ can be limited. Haitjema and Woerlee (1989) used this method and showed that tin oxide coatings can be anisotropic and that a surface layer must be assumed in a model to achieve consistent result, unless the surface is polished.

Spectroscopic Ellipsometry

With spectroscopic ellipsometry, measurements at a same location on a specimen are taken at several, or at continuously scanned, wavelengths. This increases the number of measured parameters; however, many parameters are also wavelength dependent, so in that not much is gained. However, clearly one parameter does not change: the thickness of coatings on the surface.

Calculation of Substrate and Thin-Film Parameters

In general there are no straightforward equations that relate the measured ellipsometric angles to thin-film thickness and/or optical constants. The few cases for which an analytic solution exists are given by Azzam and Bashara (1977). However for the general case, optical constants must be obtained by fitting a model to the obtained ellipsometric angles. The ellipsometric angles of a thin-film/substrate system can be calculated using the Fresnel coefficient and using a thin-film model. This is described in classical textbooks (Azzam and Bashara 1977; Jackson 1998; Heavens 1991). For more complicated multiple-film systems, a matrix method is developed. Fresnel coefficients of an anisotropic material are given by Haitjema and Woerlee (1989).

Bare Substrate

For a bare substrate, only two parameters are to fit: the real and complex part of the complex refractive index $\boldsymbol{n} = n - ik$ of the substrate. For this case in air ($n_{\mathrm{air}} = 1$), there is an analytical solution:

$$\widehat{n} = \tan(\theta)\sqrt{1 - \frac{4r}{(1+r)}\sin^2\theta} \tag{2}$$

where r is the complex number as calculated in Eq. 1.

Single Thin Film

The single-film model is relatively straightforward, especially for the case of a transparent film on a transparent substrate with a known refractive index. In that case the film thickness and refractive index can be obtained by measuring the ellipsometric angles at a single angle of incidence. For a few cases there are analytical solutions that directly relate film thickness and refractive index to the ellipsometric angles.

Anisotropic and Multiple Films

The determination of anisotropy in a film is shown by Haitjema and Woerlee (1989). In general multiple films give high parameter correlations when all parameters of every film are to be determined. Often, optical properties are quite well known, e.g., a SiO_2 coating on Si, so in that case ellipsometry is mainly used for film thickness determinations.

Applications in Chemistry and Biology

Further applications are in physical/chemical/biological phenomena at surfaces. Because of its extreme sensitivity, an ellipsometer gives an immediate response if "something" happens at a surface: a thin film grows, a clean surface oxidates, a chemical reaction appears, blood coagulates, etc.

Advantages of Ellipsometry

Accuracy

The ellipsometric angles can be determined quite accurately and rather independently on absolute intensity. Several reversal and calibration methods are available so the ellipsometric angles can be obtained accurately and bias-free.

Sensitivity

An ellipsometer can be highly sensitive. The sensitivity for a film thickness can be of the order of 1°/nm for the sensitivity of Δ for a film thickness or a change in film thickness. As ellipsometric angles can be measured with about 0.01° uncertainty for a good-quality ellipsometer, the deposition of monatomic layers can be detected.

Contactless

Obviously, ellipsometry is a noncontact measurement method. By applying windows, measurements can be carried out with the specimen in process or in a vacuum.

Disadvantages of Ellipsometry

Sensitivity

The sensitivity can be a disadvantage when measurements of less ideal specimens are needed. A thin-film measurement can easily be disturbed by a small roughness of the top of a coating. A measurement of a substrate is easily disturbed by a small roughness or oxide/water layer of a few atoms. If these effects are not taken into account in the calculation, quite erroneous values can easily be obtained.

Model Dependence

If the model consists of two coatings with two thicknesses, a calculation will give two refractive indices and two thicknesses. If the model consists of one anisotropic film, a calculation will give values for anisotropy. As the method is indirect and model-dependent, there is no warning against erroneous or nonsensical results, e.g., an ellipsometric measurement can give a high value for the extinction coefficient of a substrate while it is obviously transparent, meaning that the extinction coefficient must be effectively zero and should be fixed so in the model used.

Ellipsometry and Traceability

For this item there are different approaches. The straightforward approach is that a measurement is just a measurement of angles, so the traceability is in the traceability of the angles, combined with the wavelength/frequency of the light source used.

A different approach is considering the ellipsometer as a system that measures a specific thin film. As a reference material a thin film is supplied with a calibrated thickness and the user is supposed to measure that same thickness on his ellipsometer.

Because the results are very dependent on the assumed model of the measured surface, traceability and uncertainty of the measured angles Ψ and Δ are far easier to guarantee than, for example, a film thickness or a refractive index.

Cross-References

► Accuracy
► Traceability

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Elongating

► Stretching

Emergent Synthesis

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Synonyms

Co-creation; Interactive manufacturing

Definition

Emergent synthesis draws a way of outlook on handling complex artifactual systems, where the local interactions between the artifacts of the system form the global behavior through bottom-up development to achieve the purpose of the whole system. The emerging global order of the system structure can be modified in a top-down way from the perspective of the global purpose to the artifacts. Thus, emergence-related approaches are developed with both bottom-up and top-down features offering efficient, robust, and adaptive solutions to the problem of synthesis. While taking into account the local and global goals, the artifacts have to build up their emerging behavior, resulting in the global order of the system. Behavior of the artifacts formed depends on the designer's specification and creativity.

Theory and Application

Problem Difficulties in Synthesis

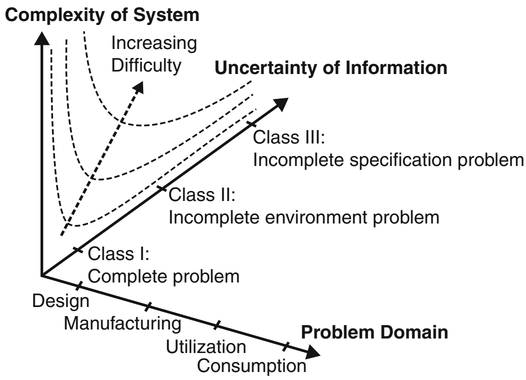
Emergent synthesis introduces three types of classes and their possible emergence-related approaches to describe whether completeness of information could be achieved in the description of the environment and in the specification of the purpose of the artifactual system.

Class I Type Problems

In class I type problems, the description of environment and specification is complete and the problem is completely described. However, in most cases, there are too many candidates of feasible solutions due to combinatorial explosion. For this type of problems, evolutionary computation methods, such as genetic algorithms, genetic programming, evolutionary strategies, and evolutionary programming, have been successfully applied.

Class II Type Problems

In class II, the description of the environment is incomplete and the specification is complete. The problem is to cope with the dynamic properties of the unknown environment. To deal with this problem, it is required to detect the resulting constraint through interaction with the dynamic environment. Learning and adaptation-based approaches such as reinforcement learning,



Emergent Synthesis, Fig. 1 Classification of synthesis problems and problem domains

adaptive behavior-based methods are feasible to this class of problems.

Class III Type Problems

In class III, not only the environmental description but also the specification is incomplete. Besides ascertaining the dynamic environmental constraints, this class has to cope with the iterative determination of the system structure. Further emergent properties, such as interactivity, self-coordination, co-evolution, and self-reference, are essential.

As shown in Fig. 1, the problem becomes more difficult as the system complexity and/or informational uncertainty increases. The figure also indicates the problem domains, since synthesis is indispensable not only in design of artifacts but in almost all the other domains of artifactual activities as well.

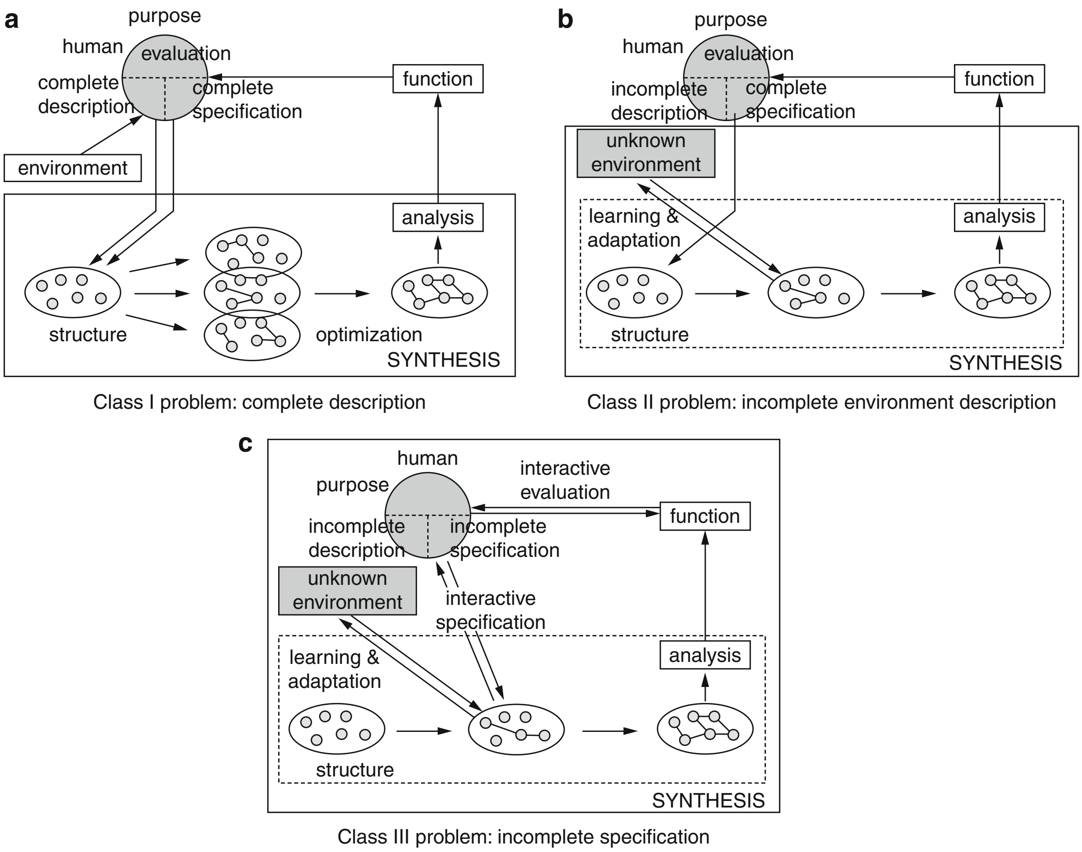
Emergent Synthetic Approaches

Instead of the traditional, analytic, deterministic approaches based on the top-down problem decomposition, like operational research, symbolic artificial intelligence, knowledge-based engineering, etc., the emergence-related approaches are being developed with both the bottom-up and the top-down features, which include evolutionary computation, self-organization, behavior-based methods, reinforcement learning, multi-agent systems, etc. and they seem to be feasible for offering efficient, robust, and adaptive solutions to the problem of synthesis.

Figure 2 shows a schematic view of the emergent synthetic approaches to problems assigned into three classes as presented above. For class I, since the specification of purpose and the constraints due to environment are fixed, the problem is completely known from the very beginning. However, in most cases, there are too many candidates of feasible solutions, and this leads to combinatorial explosion, typically to so-called NP hard problems. Therefore, it is essential to develop efficient, robust search methods to find optimal solutions. For this type of problems, evolutionary computational methods such as Genetic Algorithms, Genetic Programming, Evolutionary Strategies, and Evolutionary Programming have been successfully applied. One can use such emergence-related algorithms as problem solvers. Hence, this class of models can be characterized as fixed both in its syntax and semantics.

In class II, in spite of the fixed specification, the lack of information about the environment causes unpredictable constraints in solving the problem. To deal with this problem, it is required to be capable to detect and adapt to the resulting constraint through interaction with the environment during the system runs. Learning and adaptation-based approaches such as reinforcement learning, adaptive behavior, and behavior-based are feasible for this class of problems. Fixed semantics and adaptive syntax characterize the model in this class.

Class III problems encounter, in addition to the lack of the environmental information, the difficulty caused by the ambiguity of human intention. This class has to cope with the iterative determination of the structure of the system, and the human as a designer should be included through the interactive specification. Therefore, in order to realize human participation in the design of the target system (object) including the designer itself (subject), further emergent properties such as interactivity, self-coordination, co-evolution, and self-reference are essential. Here, multi-agent-based approaches would also be effective once the system includes the observer as well as the observed. Adaptive syntax and interactive semantics can characterize the model in this class.



Emergent Synthesis, Fig. 2 Framework for synthesis problem classes and emergent approaches to them

Application

A Survey of Emergent Synthesis Methodologies in Literature Related to Manufacturing

About 300 papers published in CIRP annals and related conference proceedings during 1990–2001 were surveyed and categorized into the three classes above (Ueda et al. 2001). Table 1 shows the total number of surveyed papers in terms of concept, theory or model, and application or realization.

Emergent Synthesis, Table 1 The numbers of reviewed papers in terms of problem classification (Ueda et al. 2001)

	Concept	Theory/Model	Application/ Realization
Class I	0	28	43
Class II	28	122	15
Class III	16	11	0
General topics	42		

Examples of Application Studies

Emergent synthesis has been applied to various research areas. For example, the problem of process planning and scheduling is solved by emergent synthesis approach (Ueda et al. 2004, 2007), and issues in supply network is also treated using emergent synthesis idea (Ueda et al. 1999; Teti and D'Addona 2006). Furthermore, extending it to even broader areas, value creation problems are treated (Ueda et al. 2008).

Potential Fields of Application of Emergent Synthesis

The idea of emergent synthesis is fundamental and thereby relates all acts of creating artifacts, so that it can be theoretical basis for various production activities. Emergent synthesis can be also applicable to the following topics as potential fields:

- Co-creation
- Personalization
- Inclusive design
- Collective intelligence
- Value creation network
- Service design
- Open innovation

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Emulation

▶ Simulation of Manufacturing Systems

End-of-Service Life

▶ EOL Treatment

End-of-Use

▶ EOL Treatment

Energy Density

▶ Specific Energy

Energy Efficiency

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Definition

Energy efficiency is the ratio between the useful energy output and the energy input of a thermodynamic system.

Theory and Application

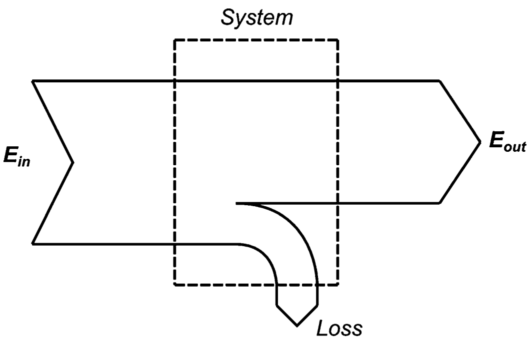
Introduction

The energy efficiency metric originates from the early development of thermodynamic cycles, such as the steam engine and internal combustion engine. However, the metric can be applied to any thermodynamic system. It serves as a performance criterion of the corresponding system. Figure 1 illustrates a generic energy flow diagram of a thermodynamic system, with the system boundary shown by the dashed line.

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

$$\eta = \frac{E_{out}}{E_{in}} \tag{1}$$

Besides this thermodynamic definition of energy efficiency, other relevant definitions



Energy Efficiency, Fig. 1 General energy flow in a thermodynamic system

include the "physical-thermodynamic" definition or the "energy consumption intensity" (Patterson 1996; Tanaka 2008). In this normalized measure, the energy efficiency is expressed as shown in Eq. 2 or its inverse. In Eq. 2, the unit of the numerator is application specific, for example, dried mass (kg), number of parts, heated volume, etc., while the denominator is the energy input.

$$\eta = \frac{physical\ useful\ output}{E_{in}} \quad (2)$$

Applications in Production Engineering

In production engineering, the system of interest is usually the production machine and/or the production system. Unlike energy conversion devices, the main objective of production machines is not to transform energy, but to manufacture products. Thus, the useful input energy, such as fuel and electricity, is lost as low-grade heat in exchange for final services of manufacturing products. These systems are also considered to be passive systems (Cullen 2009).

For systems like a production machine, the minimum work required for the corresponding process can be employed to identify the efficiency of the process (Gutowski and Sekulic 2011). Comparison between this theoretical energy with the real required energy serves as energy efficiency metric of the process. The theoretical nature of the numerator, as shown in Eq. 3, makes this definition an absolute measure of efficiency.

$$\eta = \frac{E_{theoretical}}{E_{in}} \quad (3)$$

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Energy per Unit Mass

▶ Specific Energy

Engagement Conditions

▶ Grinding Parameters

Engineering Ceramic

▶ Ceramic Cutting Tools

Environmental Cost-Effectiveness

▶ Eco-efficiency

Environmental Impact

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Synonyms

Environmental issue

Environmental effect, environmental damage, and environmental consequence are sometimes used as synonyms of environmental impact although they are located later in the causality chain that links an activity to its consequences. The activity (e.g., burning of fossil fuels) may cause an impact (e.g., increase of the concentration of the greenhouse gas carbon dioxide in the atmosphere) that leads to an effect (increased radiative forcing of the atmosphere) that as a consequence has an increased global average temperature in the atmosphere which as a consequence has sea-level rise leading to damage to coastal land ecosystems (Hauschild and Wenzel 1998). Some confusion about the terms stems from the fact that the effect of one impact becomes in itself an impact with other effects and so forth along the cause-effect chain (see example of cause-effect chain in Fig. 1).

Definition

An environmental impact is an impact that an activity has on the environment through the emissions or use of resources that it causes. In the context of life cycle assessment (LCA), an environmental impact has been defined in EC-JRC (2011) as:

> Potential impact on the natural environment, human health or the depletion of natural resources, caused by the interventions between the technosphere and the ecosphere as covered by LCA (e.g., emissions, resource extraction, land use).

Theory and Application

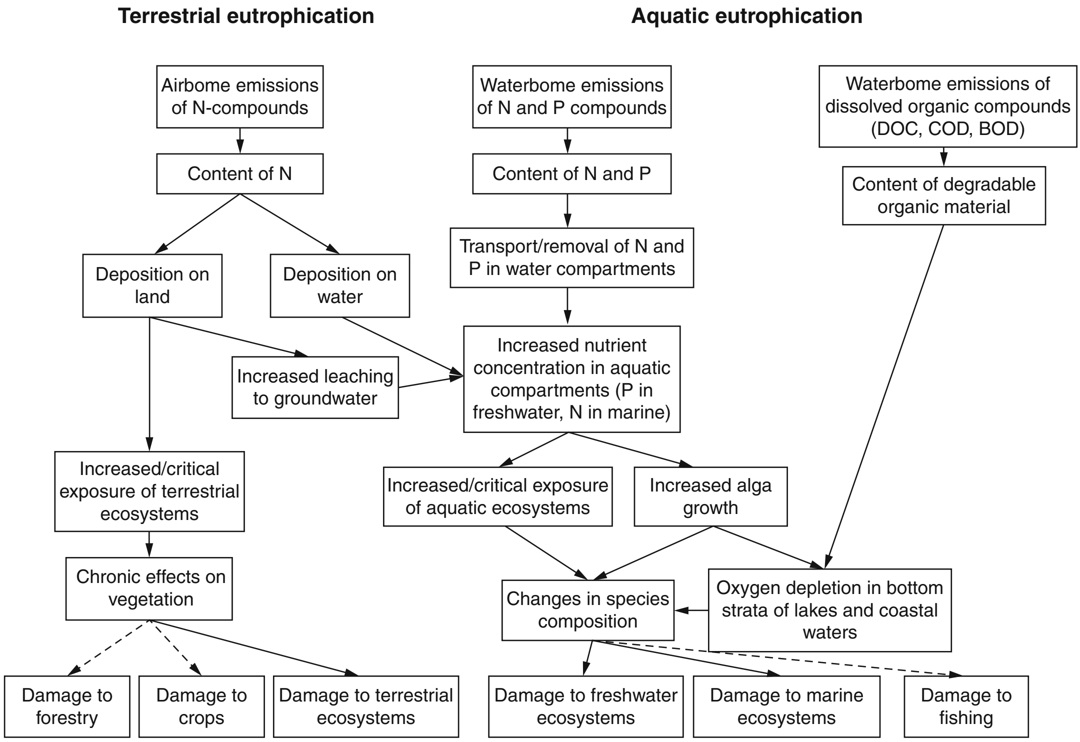
There is a nearly endless number of possible environmental impacts causally interconnected through environmental impact pathways or cause-effect chains (see example in Fig. 1 for the impacts associated with emissions of N- and P-compounds causing eutrophication of the environment). Life cycle assessment attempts to address all relevant impacts of a product life cycle (ISO 2006) and has therefore had to develop a systematic approach to the classification of environmental impacts and the quantitative expression of how large an environmental impact is caused by an emission or a physical intervention.

Impacts that are causally linked and contribute to a known environmental issue or theme are combined in an impact category, where they are represented by an impact indicator chosen somewhere along the impact pathway. Understanding of the impact pathway is fundamental for deciding whether an impact belongs to the category and to know whether different impacts are complementary or just two different links in the same impact chain (i.e., one leads to the other).

For the use in LCA, several default lists of impact categories have been produced over the years. The latest authoritative list is from the European Commission's ILCD guidelines, and it operates with the following categories:

- Climate change
- Ozone depletion
- Human toxicity, cancer effects
- Human toxicity, noncancer effects
- Particulate matter/respiratory inorganics
- Ionizing radiation, human health
- Ionizing radiation, ecosystems
- Photochemical ozone formation
- Acidification
- Eutrophication, terrestrial
- Eutrophication, aquatic
- Ecotoxicity
- Land use
- Resource depletion, water
- Resource depletion, mineral, fossil, and renewable

These are mainly (apart from the last three) emission-related impacts that may be relevant for



Environmental Impact, Fig. 1 Causality chain linking emissions of N- and P-compounds to their environmental impacts and eventual damage to ecosystems. Every impact is at the same time an effect of the impact that precedes it in the chain and the cause of the impact that follows it in the chain (Adapted from EC-JRC (2010))

assessment of impacts of a product (LCA), but there are also be other environmental impacts that may be relevant to consider. This may be the case with local impacts from noise, vibrations, smell, or light surrounding an activity.

Impacts on biodiversity are also a strong concern in times where the rate of species extinction is elevated high above previous levels. In the cause-effect chains, impacts on biodiversity are typically located toward the end, where damage on ecosystems and habitats occurs.

Cross-References

▶ Environmental Impact Assessment
▶ Sustainability

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Environmental Impact Assessment

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Synonyms

Environmental Impact

Definition

Environmental impact assessment is the assessment of environmental impacts that are caused by an activity or a decision.

The assessment of environmental impacts can be performed in different contexts of which three of a fundamentally different nature can be identified:

EIA – Environmental Impact Assessment is *"… the evaluation of the effects likely to arise from a major project (or other action) significantly affecting the environment. It is a systematic process for considering possible impacts prior to a decision being taken on whether or not a proposal should be given approval to proceed"* (Jay et al. 2007).

EIA is thus a process tool involving environmental analysis but typically also public hearing and entailing a comparison of alternatives. It is often required by environmental and planning authorities to be used prior to decisions about infrastructure changes or construction of major production facilities. In its analysis of environmental effects (not impacts), it is normally highly site specific and addresses the effects that can be expected in the local environment as a consequence of the change that is analyzed (Jay et al. 2007).

ERA – Environmental Risk Assessment is assessment of environmental risks associated with a given activity. Risk assessment combines an assessment of the potential damage (or hazard) and the probability that the damage will occur (the hazard will be realized). Environmental Risk Assessment addresses the risks to human health and ecosystem function associated with emissions of chemicals to the environment. It is focused on characteristics of the chemicals predisposing their toxicity, persistence in the environment and ability to accumulate in living organisms, and on characteristics of the environment of importance for the exposure of humans and ecosystems to the chemicals. ERA can be done as a site-specific assessment of the risk of adverse effects in a local environment from emissions caused by a certain activity. ERA can also be done in a site-generic form where the potential risk of adverse effects of a chemical in the general environment is assessed.

LCIA – Life Cycle Impact Assessment is a phase of the life cycle assessment methodology that is *"aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product"* (ISO 2006).

LCIA operates on the inventory of elementary flows for the product life cycle (input of resources and output of emissions) into potential impacts on the environment. These inventory flows are translated into scores for indicators that represent impact on human health, natural environment, and natural resources within a number of predefined impact categories (EC-JRC 2011).

The outcome of the LCIA is an environmental impact profile for the product showing its potential impacts as indicator scores for each of a number of categories of ▶ environmental impact.

The last form of environmental impact assessment is assumed to have the strongest relevance for the users of the CIRPedia, and the rest of the entry is hence focused on the environmental impact assessment performed as part of a life cycle assessment in support of environmental assessment of products, services, systems, or technologies.

Theory and Application

An international standard has been developed for the assessment of environmental impacts in LCA as part of the standardization of the methodological foundation (ISO 2006). The standard lays down the structure and principles which are generally acknowledged and followed by all LCIA methodologies today.

LCIA According to the ISO Standard Framework

According to the standard, the impact assessment proceeds through a number of steps:

First the categories of environmental impact to address are defined or – typically – chosen among already defined and developed categories of impact (see ► Environmental Impact entry for default list of impact categories in LCIA). The selection of impact categories shall be consistent with the goal and scope of the study and reflect a "comprehensive set of environmental issues related to the product system being studied, taking the goal and scope into consideration" (ISO 2006).

Then the elementary flows from the inventory are assigned to the different categories of impact, each of which is represented by an impact indicator (see ► Environmental Impact entry for default list of impact categories in LCIA). This step is called *classification* of the inventory flows.

Next step is *characterization* where a quantification of the contribution of the elementary flows to the total impact score for the category is calculated using characterization factors. A characterization is a quantitative expression of the substance's specific ability to impact on the indicator of the impact category. It is calculated using quantitative models of the impact pathway connecting the elementary flow to the impact indicator ("characterization models"), and it is mainly determined by the inherent properties of the substance. Sometimes it is expressed as an equivalent emission of a reference substance for the impact category (for the impact category global warming as kg CO_2-equivalents/kg substance). Characterization is performed as a simple multiplication of the inventory flow and the characterization factor. The resulting indicator scores are summed across elementary flows within the impact category and a total result is obtained (e.g., the total global warming potential for the life cycle expressed as kg CO_2-equivalents for the product). The collection of category indicator results for the different impact categories is the *environmental impact profile* of the product.

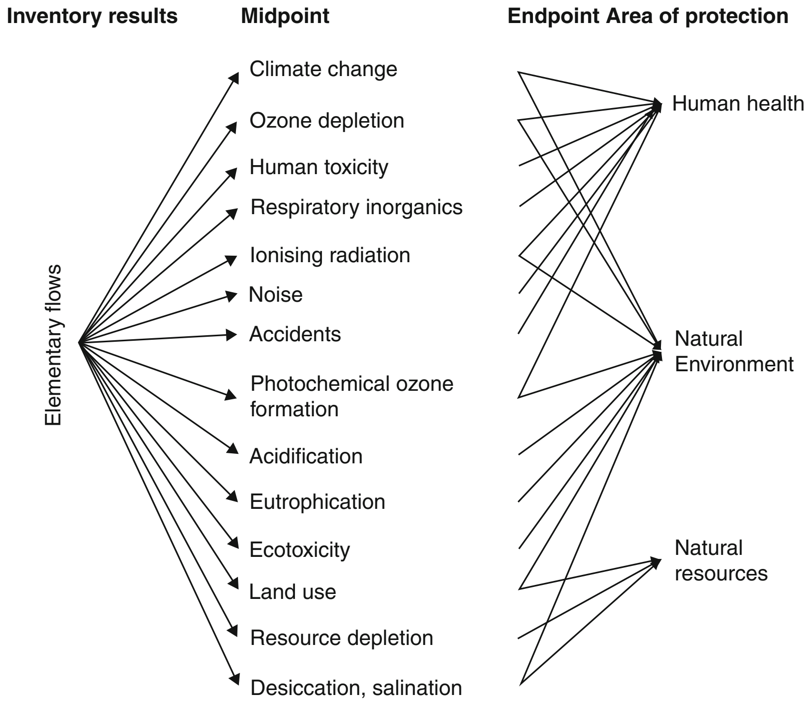
The third and fourth steps are voluntary and support comparison across impact categories (where the first two steps support comparison and aggregation within the impact categories).

The third step is *Normalization*, where the indicator results from the characterization step are related to a common set of reference information. Frequently, the current level of impact from society within each impact category is chosen as reference information, e.g., expressed as person equivalents, i.e., the annual impact from an average person (Hauschild and Wenzel 1998). Normalization brings all scores on a common scale, expresses them in a common metric, thereby making it easier to relate them to each other and preparing for the likewise voluntary valuation or weighting.

Valuation is the fourth and final step of the LCIA. It is a voluntary step that is normally performed to support conclusion and decision making based on comparative LCAs where there are trade-offs between the results for individual categories of impact (i.e., none of the alternatives is the absolute preference, outperforming the others on all category indicator results). It can be done as a weighting assigning quantitative weights to all category indicators, but it can also be a more qualitative ranking or grouping of the category indicators. It involves subjective choices, and in LCA studies supporting comparative assertions disclosed to the public, the ISO standard does not allow the use of weighting (ISO 2006).

LCIA Methods

The indicator can be chosen anywhere along the impact pathway from inventory result to the final endpoint, human health, natural environment, or natural resources. Two complementary schools



Environmental Impact Assessment, Fig. 1 Midpoint and endpoint impact categories according to the European Commission's ILCD guidelines (Adapted from EC-JRC 2010)

of approaches to LCIA exist in current practice (Hauschild 2005): Midpoint approaches and Endpoint approaches, distinguished by the location of the indicators, they choose for modeling the environmental impacts. Endpoint approaches choose their indicator at the endpoint and hence operate with very few impact categories, typically one for human health damage, one for damage to the natural environment, and one for damage to natural resources.

The midpoint approaches choose indicators at some midpoint in the impact pathway. EC-JRC (2011) argues that the midpoint indicator should ideally be located at that point of the impact pathway where the paths of individual contributors converge, i.e., the earliest point of the impact pathway beyond which there is no distinction in the impact mechanism for the contributing inventory flows. For climate change, the radiative forcing indicator (used for calculation of the GWP) respects this principle. Some of the other impact categories are more heterogeneous, in particular, the toxicity-related categories, and then it may not be possible to choose the midpoint following this principle. Here the midpoint is typically chosen as close to the endpoint as it is reasonable considering the trade-off between the wanted reduced uncertainty of interpretation (relative to the endpoint) and the unwanted increased parameter and model uncertainty.

This trade-off is also observed when choosing between midpoint and endpoint methods (Bare et al. 2000; Hauschild 2005). The latter have the strength of aggregating many of the midpoint scores into fewer scores based on environmental science modeling making interpretation and decision making easier and less dependent on normalization and weighting. On the other hand, the models applied to calculate the endpoint scores are so uncertain, immature, or deficient for many of the midpoint impact categories that based on the most comprehensive review of LCIA methods performed to date, the current guidelines from the European Commission largely refrain from giving recommendations of LCIA methods at endpoint level (EC-JRC 2011; Hauschild et al. 2012). Figure 1 shows midpoint and endpoint impact categories and their relation.

A number of LCIA methods have been developed over the last 20 years, both midpoint methods (e.g., *CML 2002* (Guinée et al. 2002), *EDIP97* (Hauschild and Wenzel 1998), *EDIP 2003* (Hauschild and Potting 2005), Swiss Ecoscarcity (Brand et al. 1998) and *TRACI* (Bare et al. 2003)) and endpoint methods (*EPS* (Steen 1999a, b), *Eco-indicator 99* (Goedkoop and Sprinsma 2000)), or combinations of the two (*LIME* (e.g., Itsubo et al. 2004), *IMPACT 2002+* (Jolliet et al. 2003) and *ReCiPe* (Goedkoop and De Schryver 2009)). EC-JRC 2010 gives a recent and consistent presentation of most of the existing LCIA methods.

Cross-References

▶ Environmental Impact
▶ Sustainability

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Environmental Improvement Cost

▶ Eco-efficiency

Environmental Intensity of Production

▶ Eco-efficiency

Environmental Issue

► Environmental Impact

Environmental Productivity

► Eco-efficiency

Environmentally Benign Manufacturing

► Cleaner Production

EOL Treatment

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Synonyms

End-of-service life; End-of-use; EOSL; EOU

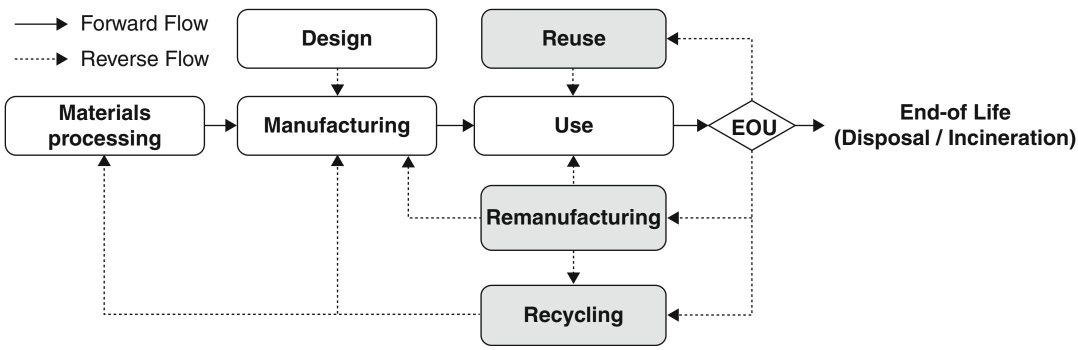
Definition

The end-of-life (EOL) of a product has traditionally been recognized as the point when a product no longer satisfies the needs or expectations of a user. The phrase "end-of-life" is a misnomer since a product at this point may still have considerable functional or material value. A product that someone no longer wishes to use should be thought of as having reached the end of a use cycle, i.e., an end-of-use (EOU) product. An end-of-use product often still has significant functional and material value remaining that can be recovered through reuse, remanufacturing, refurbishing, or recycling. The value of an EOL product varies considerably depending on its condition, quality, and cost to recover the product. At the true end-of-life of a product, any materials of value might be recycled while the remainder is incinerated or disposed in a landfill (Fig. 1).

Theory and Application

The design of products, and in fact the planning of the whole life cycle, must consider the management of end-of-use (EOU) products and how they will be processed. Product design for end-of-use should consider how products are recovered, management of individual components, disassembly procedures, as well as the evolving value/health of a product and its components as the product is used. Considering EOU early in the design process allows potential recovery opportunities to be identified (Herrmann et al. 2008). Hence, the design for disassembly (DfD), design for recycling (DfR), design for sustainability (DfS), design for environment (DfE), design for life cycle (DfLC), and design for end-of-life (DfEOL) are strategies created to avoid or mitigate the negative environmental impacts of products during their life cycle and manage the end-of use phase of products. These strategies, when added to other manufacturing practices such as component identification, modularity, and an increased use of recycled materials, could contribute significantly to the recovery of products at end-of-use.

Regardless of the design technique used, the traditional EOU recovery options generally considered are reuse, refurbishing, remanufacturing, and recycling (Ilgin and Gupta 2010; Lee et al. 2010). Each of the EOU options has a different purpose as well as advantages and challenges. For instance, the reuse, refurbishing, and remanufacturing strategies extend the operational



EOL Treatment, Fig. 1 Product life cycle and end-of-use alternatives

life of the product and preserve the functional value added during manufacturing as well as the material value inherent to the components. In the case of repairable systems, these strategies can be useful to meet the demand for spare parts and reduce the time required for a customer to receive a product. Historically, however, reused, refurbished, and remanufactured components have been associated with lower quality, uncertainty about performance, shorter warranty periods, and costly maintenance. These are perceptions that must be overcome and constitute a challenge for recovery companies and future research. Unlike reuse, refurbishment, and remanufacturing, a recycling EOU strategy only recovers the material value embedded within a product, and any product functional value is totally lost (Srivastava 2007; Pigosso et al. 2010). However, significant benefits still exist for recycling, especially for products containing materials that have high value in secondary material (scrap) markets.

The EOU recovery process involves retrieving residual functional or material value, which often offers considerable economic and environmental benefits. Take-back legislation, market requirements, and used product value are the main drivers for EOU recovery (Sasikumar and Kannan 2008). For EOU products, reverse logistics are often a critical consideration. Reverse logistics (RL) is the process associated with managing the flow of products, components, and materials from the point where a product that reaches the end of a use cycle to a point where the product is processed for future use. Successful management of used products requires planning of reverse logistics operations. The selection of collection points, logistics of transportation, disassembly, inspection, classification, and reconditioning among other operations are good examples of critical activities that must be planned in advance.

Take-Back Policies and Regulations

Historically, the recovery of used products has been either market driven or policy driven. In the case of the latter driver, government action has been motivated by the desire to reduce discharges to landfills, lower the quantity and environmental impact of industrial waste streams, and respond to community pressures. Often policies and regulations that have emerged relate to product end-of-use and have included such topics as:

- Waste Electrical and Electronic Equipment (WEEE). WEEE regulations seek to establish responsibilities for EEE manufacturers at EOU and promote the recycling and reuse of electric and electronic devices.
- Restriction of Hazardous Substances (RoHS). RoHS regulations are focused on avoiding and reducing the use of heavy metals and other hazardous substances that could discourage or make complex the recovery of the product at EOU.
- End-of-Life Vehicles (ELV). ELV regulations aim to make the recovery, dismantling, and recycling of vehicles and their components more environmentally friendly and encourage original equipment manufacturers to design vehicles suitable for recycling. For instance,

in the case of Japan, a consumer pays a fee at the time of purchase, and when, at the end of a use cycle, the consumer sells the car to a dealer, the fee is reimbursed. Dealers take back and recycle around 83 % of the vehicle by weight, e.g., engines, tires, seats, and steel components are recovered. The remaining automobile residue has been employed to create artificial islands (Kumar and Yamaoka 2006).

- Packaging. Packaging regulations seek to reduce the volume and weight of packaging either during transportation or secondary packaging to the minimum required (Nakajima and Vanderburg 2006).

The incorporation of take-back policies should be an initiative shared among a diversity of entities including the original equipment manufacturers (OEMs), government, recovery companies, distributors, and even customers. Beyond the policy framework, new paradigms must be established in order to promote sustainable products and closed material loops at product end-of-use. In this sense, concepts such as Product Service Systems (PSS) and Producer Responsibility Organization (PRO) could support this purpose.

The philosophy of Product Service Systems (PSS) is to meet customer needs through provision of a service (e.g., transportation) as opposed to selling a tangible good (e.g., a car). In either case the functional need is met, but the customer purchases the service rather than a product (Maxwell and van der Vorst 2003; Mont and Lindhqvist 2003). With the PSS approach, products are usually leased or rented rather than sold to a consumer. The maintenance, reconditioning, and upgrading of the physical product are the responsibility of the product owner and not the consumer.

The Producer Responsibility Organization (PRO) is a collaborative approach that seeks to share the cost, risk, and responsibility of waste management among two or more producers with a set of waste reduction goals (Nakajima and Vanderburg 2006; Fleckinger and Glachant 2010). Under this approach, a centralized not-for-profit organization is in charge of collecting and processing end-of-use products on behalf of their individual members.

Cross-References

▶ Recycling
▶ Remanufacturing
▶ Reuse

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EOSL

▶ EOL Treatment

EOU

▶ EOL Treatment

ERP Enterprise Resource Planning

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Synonyms

PPC; Production planning and control

Definition

Enterprise Resource Planning (ERP)

The term Enterprise Resource Planning (ERP) sums up the different tasks within a company to plan and control the internal and external resources (capital, personnel, and capital equipment) of a company efficiently.

ERP System

ERP systems execute these tasks in practice and can therefore be considered the information backbone of the company. In addition to the core of Production Planning and Controlling (PPC), ERP systems integrate all entities (e.g., purchase, finance and controlling, sales) of a company and their corresponding business processes. ERP systems can be defined as business software solutions that consist of several modules such as PPC, materials planning, accounting, human resource, or logistics. They interact via a central database.

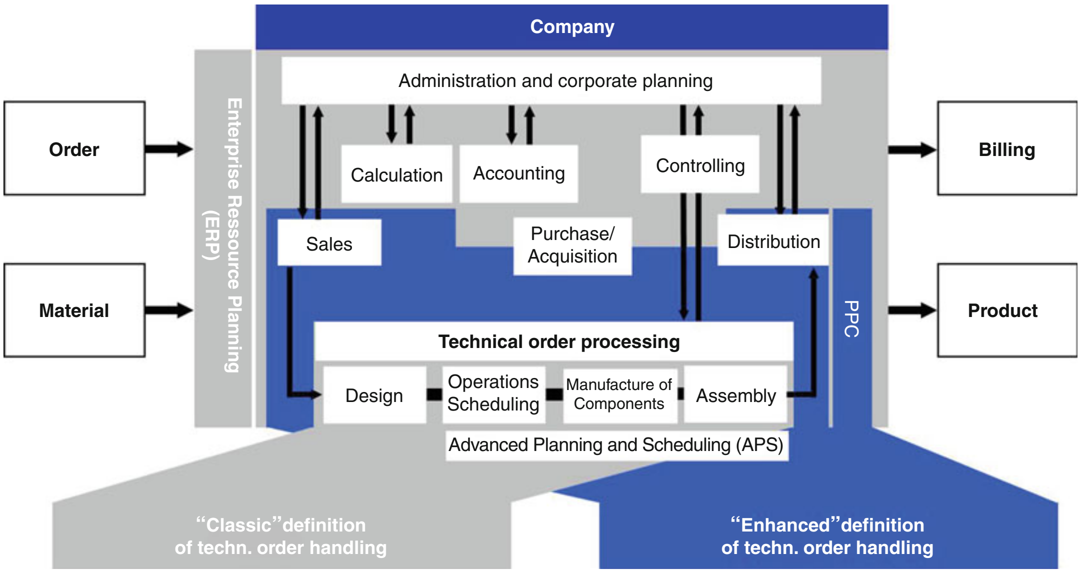
Theory and Application

Enterprise Resource Planning for Production Planning and Controlling

Order processing includes the entire range of activities which have to be performed by a company during the period between customer request and the delivery of an item.

Technical order processing, according to its *classic definition*, comprises all departments of a company which are directly involved in the fabrication of an item, starting from the placement of an order up to the final assembly of the product.

According to the *enhanced definition* of technical order processing, in addition to the departments of design, operations planning, parts production, and assembly, also the departments which act as a direct interface between customer and company (e.g., sales, distribution and purchasing) belong to the technical order processing. PPC supports the entire technical order processing from the receipt of a customer request to the delivery of the desired item and has in every field of activity the task to plan and control the process of production on a quantity, time, and capacity basis. The origin of PPC conceptions is represented by the concept of material requirements planning (MRP), which was developed in the middle of the 1960s. In addition to this one-sided material-related or rather quantity-related concept, capacity planning combined with the coordination of quantity and capacity was realized in the MRP II concept (MRP II: Management Resources Planning). The MRP II concept (Zäpfel 1994) belongs in its original form to the "traditional" control concepts (Glaser et al. 1991) with which a possibly high utilization of capacities was given special emphasis (Haupt and Nöfer 1994). A hierarchical, backwards scheduled gradual planning concept forms the basis with which the company is divided up into several planning levels. The results of one planning level form in each case the target-input for the subordinate sector. Within each level modules are responsible for the tasks of quantity planning, flow scheduling, machine load, etc. A feedback to a superior planning level is performed only in the case that a target turns out to be not feasible (Zäpfel 1994). The loading of orders on machines in the manufacturing level takes place according to priority rules (like "shortest operation time" and "first in first out – FIFO") which usually do not allow a constant fulfilment of several targets. Mostly, increased lead times have to be taken into consideration (Haupt and Nöfer 1994). Decisions which are based on long-planning periods often lead to outdated or unfeasible targets. Acceptance problems occur, due to irreproducible planning decisions on the



ERP Enterprise Resource Planning, Fig. 1 ERP and its relation to order processing, PPC, and APS

manufacturing level (Glaser et al. 1991). First, scheduling calculates against unlimited available capacities.

Over the past years, system sellers (e.g., SAP AG and BAAN) have extended their PPC systems with additional functionalities which outrange the original functionalities like quantity planning, scheduling, and capacity planning by far. Most of these add-ons affected commercial functionalities (e.g., financial accounting and controlling), thus the term "PPC" was not appropriate anymore. Many of the systems available on the market today are extensive internal information systems, so that system sellers have started to use the international term "Enterprise Resource Planning (ERP)."

Recent approaches in ERP aim at an improvement of planning accuracy. Within advanced planning and scheduling (APS), all resources (material, production facilities, and staff) are planned simultaneously in one planning run as in contrast to the approach of hierarchical gradual planning (MRP). While MRP calculates against unlimited available capacities, APS considers currently existing capacity limits for the load assignment. APS also supports a plan optimization using simulation. Different planning alternatives are evaluated with regard to conflicting optimization targets (max. utilization, setup time optimization, shortest lead time, etc.). Moreover, APS supports sales activities through real-time availability checks for customer inquiries or customer orders. Therefore, the sales department is enabled to make more realistic delivery date promises towards the customer (Fig. 1).

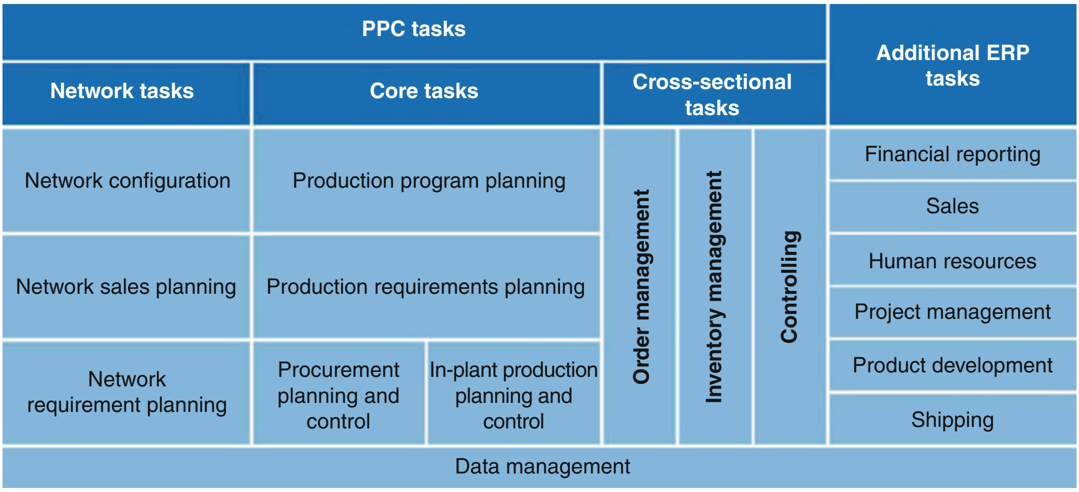
ERP Tasks

PPC Tasks

For producing companies, the planning of resources and production processes, as covered by the extended concept of Production Planning and Control, are the core functions of Enterprise Resource Planning (ERP). According to Schuh (2006), Production Planning and Control incorporates the following tasks (Fig. 2).

Network Configuration Network configuration supports companies finding their strategic position and helps them to recognize the necessity of establishing a partner network, configured by the composition of the participating companies. The strategic configuration of networks is divided into the subtasks production program planning and network design.

Network Sales Planning Network sales planning is demand oriented and distinguished



ERP Enterprise Resource Planning, Fig. 2 PPC and ERP tasks

from the local sales planning by its network character (e.g., "Collaborative Demand Planning," "Collaborative Planning, Forecasting, and Replenishment" (CPFR)). Network sales planning results in an accurate overview of the available quantities and the date of availability of products and product groups designated for sale.

Network Requirements Planning The network requirements planning should reduce the coordination efforts of the demand-based disciplines demand assessment and make or buy analysis by determining the type, quantity, and time of products to be produced. For that purpose, the requirements of material and components resulting from the sales plan need to be determined and distributed to the partners of the network to assure the fulfilment of demand. The fulfilment of demand is based on the subtasks network capacity planning, network demand allocation, and network procurement planning.

Production Program Planning The rolling and periodical production program planning determines the type, quantity, and time of products to be produced and is defined by production and sales representatives. The result is a production plan which is adjusted with regard to marketability and feasibility. The production plan defines the point of time and quantities in which products are to be produced, under the condition of maximizing profits and/or minimizing costs, also considering the capacity restrictions. Furthermore, the production program planning results in a procurement plan of material/components.

Production Requirements Planning The medium-term production requirement planning is responsible for planning the required resources based on the production program. From the primary demand, the bill of material, and the work schedule, the resource requirements are derived (dependent requirements planning). Then, the lead time scheduling derives the time relations between the production orders and generates milestones for the capacity planning. Finally, the capacity requirements planning, based on the scheduled production steps, determines the capacity requirements of the planned period. Afterwards, the capacity requirements and the available capacity are compared and, if necessary, adjusted.

In-Plant Production Planning and Control The in-plant Production Planning and Control details the production plan based on the limitations of the production requirements planning and the resulting planning flexibility and monitors its realization. The planning flexibility results from the difference of the earliest and latest start date of production and the allocation of production quantities to the respective production orders. In case of a waiting queue, the release of process steps may depend on predetermined selection criteria (e.g., priority rules) or cumulating criteria (minimizing setting-up time).

Procurement Planning and Control Procurement planning and control defines the procurement quantities and dates of parts, assembly groups, and products that need to be purchased. Therefore, the order quantity calculation determines the quantities to be purchased based on the secondary requirements and generates the orders. Later, the supplier evaluation is based on the criteria quality, compliance with delivery dates, prices, and supplier conditions.

The process of order release and order controlling transmits the orders to the respective suppliers. The orders and the delivery dates are tracked continuously and compared to actual dates of goods received. When goods are received, their type and quantity and finally their quality are checked.

Order Management The main tasks of order management are the coordination of all activities involved in the processing of orders and the synchronization of task fulfilment on the different planning levels of the PPC. The primary objective is to increase the level of transparency of order processing and to improve the flexibility when reacting to internal or external disturbances.

Inventory Management Stocks are used to compensate varying customer demands and to be less dependent of the suppliers' compliance with delivery dates. The task of inventory management within the PPC includes inventory planning, inventory analysis, warehouse administration, inventory control, batch management, and the determination of material planning parameters and strategies.

Controlling Controlling is a target-oriented fulfilment of managerial functions, which addresses the system-based search and processing of information for planning, coordination, and monitoring. The aim of the integrated controlling concept is to increase the transparency within the company and the network by mapping all relevant information to evaluate the respective performance.

Data Management Data management based on a centralized database is one of the core functionalities of ERP/PPC systems, aiming at a high quality of data in regard to currentness, correctness, and completeness. It thus avoids inconsistencies, redundancies, and media disruptions between the subsystems and provides a structure of data that enables the quick and easy access and modification of data.

Additional ERP Tasks

In addition to the tasks mentioned above, Enterprise Resource Planning consists of the following additional tasks.

Financial Reporting Financial reporting maps the finances of the company and provides the data for externals. The essential tasks are the bookkeeping and the annual statement of accounts. For bookkeeping, all significant business transactions are tracked. Furthermore, the accounts receivable, the accounts payable, and the assets accounting are documented.

Sales Sales department is responsible for the management of customer data, for the acquisition of new customers, and for the handling of offers and orders. Managing customer data includes the management of addresses and key contacts, the mapping of the structures of corporate groups, and the assignment of key accounts. The management of events and campaigns, as well as the support and coordination of correspondences, is part of acquisition. The handling of offers includes transforming a request into an offer, the determination of delivery dates and prices, and the tracking and follow-up of open offers. Handling orders comprises the tasks towards a successful order release and the respective order scheduling.

Human Resources Human resources department selects the personnel and is responsible for the staff development. It also covers the staff assignment and the personnel controlling and takes care of time management, travel expenses, the wage and salary administration, and the maintenance of staff-related master data.

Project Management Project management sets up the project plan, by defining work packages, milestones, and the project budget. Project management deals with all departments that are involved in the project and therefore plays an important role for the organization and controlling of the project.

Product Development The product development defines the shape, attributes, and the structure of products, thus determining the bill of material and partially the material master. The required attributes of parts and other aspects (e.g., measures) are specified in drawings and further bills of material, given that the parts are not standardized.

Shipping After the planning and handling of shipments, the shipping department needs to ensure that assembled products are provided to the customer in the right time and quality. Warehouse administration, the commissioning, the handling of exports and customs, and the management of returns are further responsibilities.

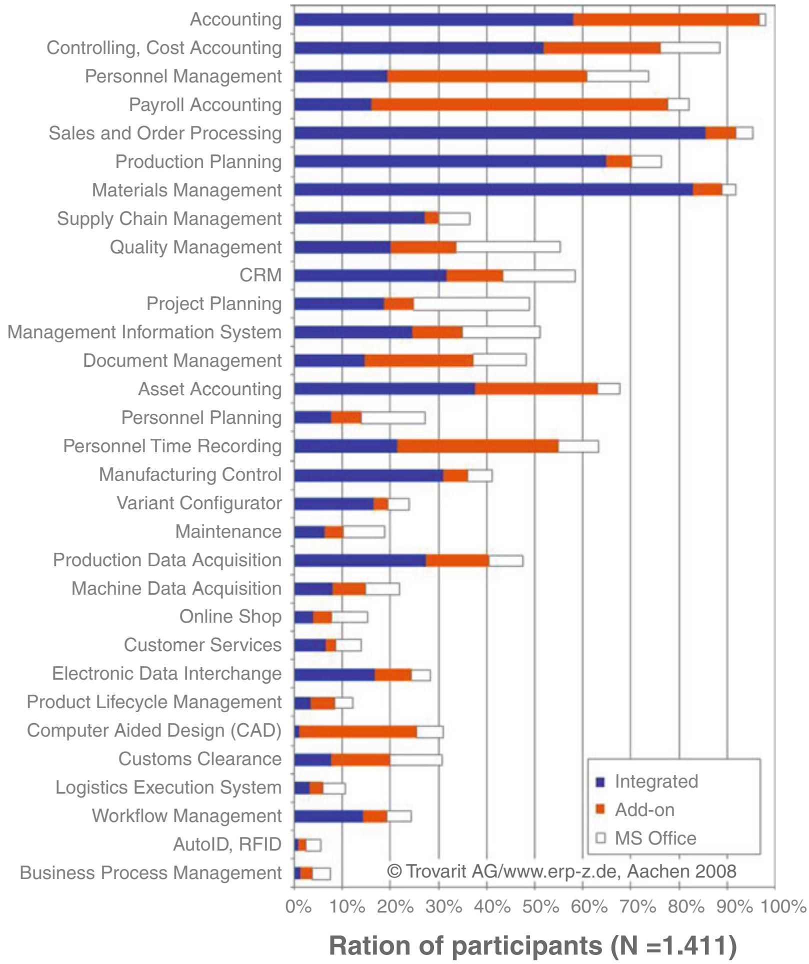
ERP Systems and Modules

In addition to ERP (core) systems, a wide variety of business application systems (ERP modules) exist that provide interfaces to these ERP systems. In this context, different variations could be noticed in the development of ERP systems in recent years. While some ERP vendors tend to integrate an extensive range of functionality into their own systems, others follow the best-of-breed approach. For this, the most appropriate ERP modules (e.g., for detailed manufacturing planning, quality management, or personnel time recording) are installed around the current ERP (core) system in accordance with defined standards. These ERP modules are developed and distributed by third-party vendors. Due to its modular structure, the software can be adapted flexibly to individual requirements depending on the field of application (Görtz and Hesseler 2007). Again, the modular structure enables every company to install only required modules based on basic software, which are essential for their specific operational needs. The different systems on the market often differ significantly in their technical focus, depending on the target industry, the size of the company, and the number of required end users, as well as the technologies being used such as, e.g., databases, programming language, and supported software platforms. Some systems are built entirely on java, while other vendors use several programming languages. Similarly, the underlying databases can vary as well. Examples are Microsoft Access, MySQL, DB2, or Oracle (Intrup 2009).

ERP systems differ also fundamentally regarding the range of offered core and extension modules. They range from nearly fully integrated systems like SAP ERP, to completely lean systems that cover missing functionalities with products from software partners (Pawellek 2007). Figure 3 gives an overview about the basic application of various ERP modules in companies (Meier and Sasu 2010).

In recent years, an increasing consolidation can be determined on the ERP market due to a series of mergers and acquisitions. Partly, this can be explained by leading vendors willing to integrate extended ERP functionality in their software products as soon as possible without having to deal with the time-consuming development process. There have already been a number of company acquisitions aiming to aquire products of software companies specialized in the field of supply chain management (SCM) and customer relationship management (CRM). Presumably, major vendors will grow at the expense of smaller and more specialized software development companies in the long term.

ERP Enterprise Resource Planning, Fig. 3 Application rate of ERP core and extension modules



Cross-References

- ▶ Capacity Planning
- ▶ Logistics
- ▶ Planning
- ▶ Production
- ▶ Production Planning
- ▶ Scheduling

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Error

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Synonyms

Error of measurement; Measurement error

Definition

Measured quantity value minus a reference quantity value

NOTE 1. The concept of "measurement error" can be used both:

(a) When there is a single reference quantity value to refer to, which occurs if a calibration is made by means of a measurement standard with a measured quantity value having a negligible measurement uncertainty or if a conventional quantity value is given, in which case the measurement error is known.

(b) If a measurand is supposed to be represented by a unique true quantity value or a set of true quantity values of negligible range, in which case the measurement error is not known.

NOTE 2. Measurement error should not be confused with production error or mistake.

(ISO Guide 99 2007, Definition 2.16)

Theory and Application

Let us start discussing the term "error" with the well-accepted definition of (ISO 99 2007), the International Vocabulary of Metrology (VIM), see definition.

In NOTE 1, we recognize two concepts:

- Reference quantity value is known.
- Reference quantity value is not known.

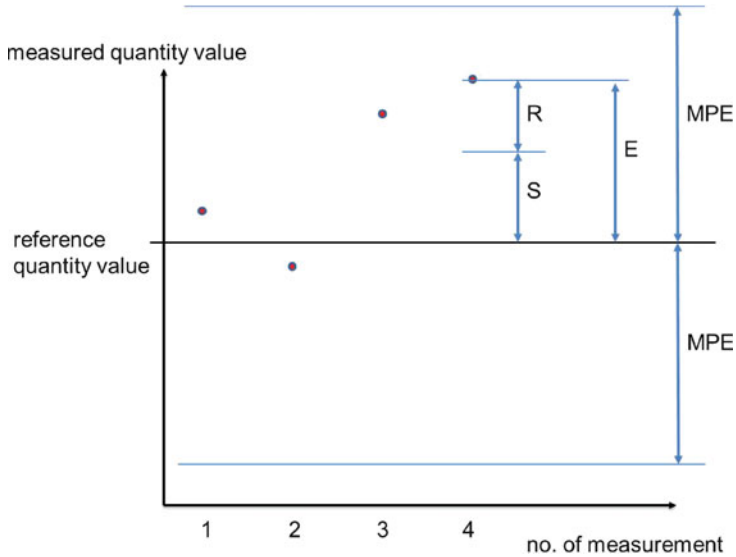
In the introduction of (ISO 99 2007), the VIM, these two concepts are named and explained in more detail:

- Error Approach (or Traditional Approach or True Value Approach).
- Uncertainty Approach.

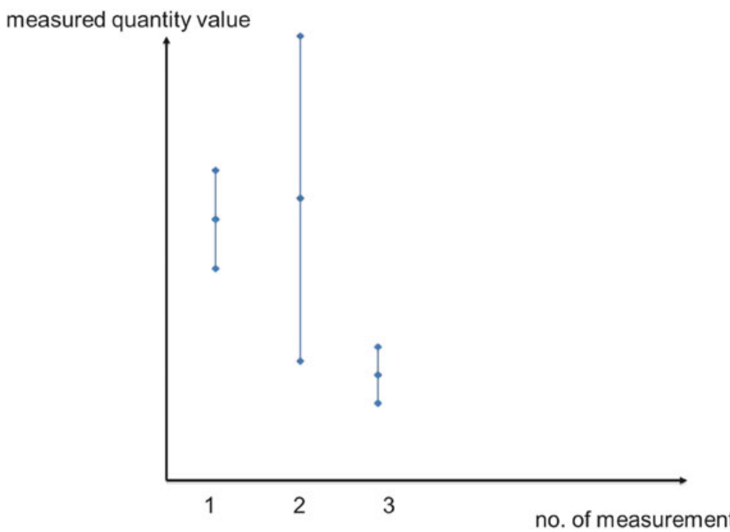
In the Error Approach, where the reference quantity value is known, the aim of the measurement is to determine an estimate of the true value that is as close as possible to that single true value. The deviations from the true value consist of random and systematic errors that have to be treated differently. There are no rules, how systematic and random errors combine to form the total error of any measurement result. Usually, the total error is estimated as an upper limit of the absolute value. This upper limit is sometimes loosely named "uncertainty."

In the Uncertainty Approach, where the reference quantity value is not known, the aim of the measurement is not to determine a true value as closely as possible, but to assign an interval of reasonable values to the measurand, based on the assumption that no mistakes have been made in performing the measurement. In this approach, the interval of reasonable values assigned to the measurand cannot be reduced to zero, because of the definitional uncertainty, which is due to the finite amount of detail in the definition of the measurand.

Figure 1 illustrates the Error Approach. Measured quantity values show an error E to a reference quantity value, the error might change for each measurement, due to the fact that we have a random measurement error component R and a systematic measurement error component S. Errors, e.g., for measuring instruments,



Error, Fig. 1 Measurement errors in the Error Approach. *E* error, *MPE* maximum permissible measurement error, *R* random measurement error, *S* systematic measurement error



Error, Fig. 2 Measurement errors in the Uncertainty Approach. Each measured quantity value is accompanied by plus/minus measurement uncertainty

might be limited by a statement on the maximum permissible measurement error MPE.

Figure 2 illustrates measurement errors in the Uncertainty Approach. Here each measurement is represented by the measured (or derived) quantity value and the measurement uncertainty (or derived uncertainty).

(ISO 98-1 2009), the Guide for Expression of Uncertainty in Measurement (GUM), focuses on the mathematical treatment of measurement uncertainty through an explicit measurement model under the assumption that the measurand can be characterized by an unique value, i.e., the definitional uncertainty is considered to be negligible in comparison to other components of measurement uncertainty. Moreover, GUM gives guidance on the Uncertainty Approach in the case of a single reading of a calibrated instrument, a situation normally met in industrial metrology.

Within the Uncertainty Approach, we speak of metrological compatibility of measurement results (ISO 99 2007, definition 2.47):

Metrological compatibility of measurement results (or metrological compatibility)
Property of a set of measurement results for a specified measurand, such that the absolute value of the differences of any pair of measured quantity values from two different measurement results is smaller than some chosen multiple of the standard measurement uncertainty of that difference.

NOTE 1. Metrological compatibility of measurement results replaces the traditional concept of "staying within the error," as it represents the criterion for deciding whether two measurement results refer to the same measurand or not. If in a set of measurements of a measurand, thought to be constant, a measurement result is not compatible with the others, either the measurement was not correct (e.g., its measurement uncertainty was assessed as being too small) or the measured quantity changed between measurements.

NOTE 2. Correlation between the measurements influences metrological compatibility of measurement results. If the measurements are completely uncorrelated, the standard measurement uncertainty of their difference is equal to the root mean square sum of their standard measurement uncertainties, while it is lower for positive covariance or higher for negative covariance.

Independent from the approach, we can distinguish between systematic and random measurement error (ISO 99 2007, definitions 2.17 and 2.19):

Systematic measurement error (or systematic error of measurement or systematic error)
Component of measurement error that in replicate measurements remains constant or varies in a predictable manner.

NOTE 1. A reference quantity value for systematic measurement error is a true quantity value, or a measured quantity value of a measurement standard of negligible measurement uncertainty, or a conventional quantity value.

NOTE 2. Systematic measurement error, and its causes, can be known or unknown. A correction can be applied to compensate for a known systematic measurement error.

NOTE 3. Systematic measurement error equals measurement error minus random measurement error.

Random measurement error (or random error of measurement or random error)
Component of measurement error that in replicate measurements varies in an unpredictable manner.

NOTE 1. A reference quantity value for a random measurement error is the average that would ensue from an infinite number of replicate measurements of the same measurand.

NOTE 2. Random measurement errors of a set of replicate measurements form a distribution that can be summarized by its expectation, which is generally assumed to be zero, and its variance.

NOTE 3. Random measurement error equals measurement error minus systematic measurement error.

Systematic measurement error is connected to measurement trueness and to measurement bias. Therefore, these two definitions are repeated (ISO 99 2007, definitions 2.14 and 2.18) in order to recognize the differences:

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.

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 bias (or bias)

Estimate of a systematic measurement error.

Furthermore, "maximum permissible error," "datum measurement error," and "zero error" are widely used and defined in ISO 99 2007, definitions 4.26, 4.27, and 4.28:

Maximum permissible measurement error (or maximum permissible error or limit of error)

Extreme value of measurement error, with respect to a known reference quantity value, permitted by specifications or regulations for a given measurement, measuring instrument, or measuring system.

NOTE 1. Usually, the term "maximum permissible errors" or "limits of errors" is used where there are two extreme values.

NOTE 2. The term "tolerance" should not be used to designate "maximum permissible error."

Datum measurement error (or datum error)

Measurement error of a measuring instrument or measuring system at a specified measured quantity value.

Zero error

Datum measurement error where the specified measured quantity value is zero.

NOTE: Zero error should not be confused with absence of measurement error.

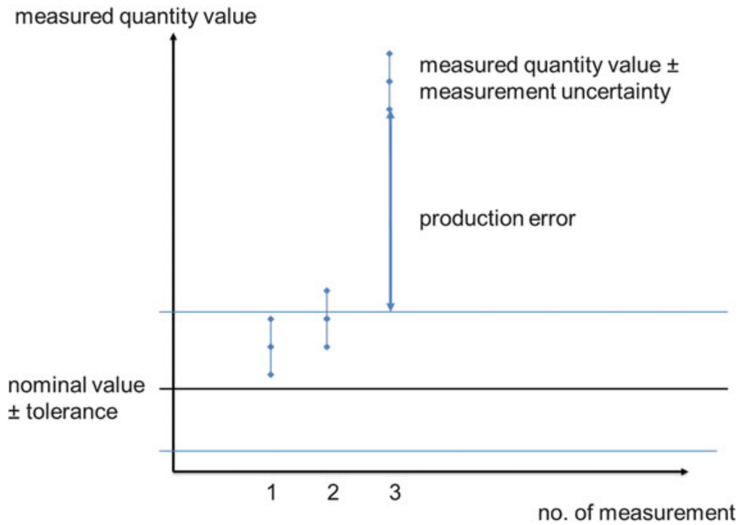
"Maximum permissible error" (MPE) is also called error bounds, error band, or error bar (Ruhm 2005a). An example for MPE is the statement of error of indication of a coordinate measuring machine (CMM) for size measurement, E (according to ISO 10360-2 2009). Any length measurement on a gauge block carried out on a CMM should stay within the stated MPE value. ISO 10360-2 2009 also described the detailed procedure, how to prove this statement.

If we get one step further and take the view of systems theory (Ruhm 2005b), any measurement error is a signal. Therefore, a measurement error may show all properties of a signal:

- The measurement error may show systematic and/or random components, which was discussed already.
- The measurement error might be time constant or time variable; if parameters of the measuring process and/or the measurement process change with time, the measurement error will also change in time; parameters of the measuring process include disturbing quantities, like variation of environmental temperature, as well as parameters of the process, like any drift caused by self-heating of the measuring instrument.
- The measurement error might be divided into a direct and an alternating component; the direct component corresponds to the arithmetic mean value of the error; the systematic measurement error might have a direct component and an alternating component, the random measurement error will have an alternating component only.
- The measurement error might be described by the mean error (arithmetic mean value), the variance of the error, but also by the mean square error, the mean error power, and the root mean square error.
- If time dependencies of the measurement error shall be considered, the error can be described by the autocorrelation function of the error, the referred autocorrelation function of the error, and/or the spectral power density function of the error.

In the view of signal and system theory (Ruhm 2011), the main groups of measurement errors are:

- The transfer response error, when the measurement process has a nonideal transfer process, like a noncorrected nonlinear behavior of a length measuring instrument.
- The disturbance quantity error, when disturbance quantities influence the measurement result or when they influence the result different from the nominal transfer function (or model), like the temperature influence on a laser interferometer length measurement.



Error, Fig. 3 Production error, tolerance zone, and measurement uncertainty. Measurement 1: product is within specification; measurement 2: fulfilling of specification not proven; measurement 3: product out of specification

- The loading quantity error, when the measurement disturbs the measurand or when the measurement disturbs the measurand different from the nominal transfer function (or model), like mechanical deformation of the measured object due to a measurement force introduced by a length measuring device.
- The disturbance/loading quantity error, when disturbance quantities change the loading quantity error, like a change of the effect of a measuring force due to a change in environmental temperature.

If we have another look at the definition of "error" (see definition), we should pay some attention to NOTE 2 of the VIM definition. This note points to the fact that error is also used outside of metrology, e.g., as "production error," which we might define as product out of specification, e.g., a ground cylinder with diameter of 20.005 mm, whereas the specification asks for a diameter of 19.997-20.003 mm (dia. 20.000 ± 0.003 mm).

Also here any measurement error is of importance. The measurement error, expressed by the measurement uncertainty, has to be applied for checking any specification: Any measurement uncertainty reduces the specification zone (or tolerance zone) according to ISO 14253-1 1998. If the measurement results in a measured quantity not within the specification zone (reduced by the measurement uncertainty), we observe a production error.

This concept is illustrated in Fig. 3. For evaluating any production error (or product error), we need a nominal value and the tolerance, as well as the measured quantity value plus/minus the measurement uncertainty.

- In measurement 1, measured quantity value plus/minus measurement uncertainty is fully within the tolerance limits. Here no production error is present, the product conforms to the specification.
- In measurement, 2 measured quantity value plus/minus measurement uncertainty is partly out of the tolerance zone. Therefore, it is not sure if there is a production error. It is uncertain that the product fulfills the specification. Measurements shall be carried out with smaller measurement uncertainty.
- In measurement 3, measured quantity value plus/minus tolerance is fully outside the tolerance zone. Therefore, we obey a production error.

For mechanical parts, we group production errors in form error (e.g., flatness error, roundness error, roughness error), size error (e.g., diameter error, pitch error of a screw), position and orientation error (e.g., distance error between two nominal parallel planes, squareness error, coaxiality error).

For machine tools, we group errors in error motions of spindles and rotary axes (e.g., axial error motion, radial error motion), error motions of linear axes (e.g., linear positioning error motion, straightness error motion, pitch error motion), contouring errors (e.g., circular error) (ISO 230-1 2012). Errors of machine tools may be also grouped according to the error source: geometric errors, errors of the numerical control, dynamic errors, thermal errors, load errors, etc.

Cross-References

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

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Error of Measurement

▶ Error

Etching

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Synonyms

Chemical machining; **CHM** – generic term for the entire family of **ch**emical **m**achining processes including chemical milling of pockets or cavities (Bellows 1977); **PCM** – **p**hoto**c**hemical **m**achining, also commonly known as photoetching, photomilling, photochemical milling, photofabrication, and chemical blanking (Allen 1986); Photochemical machining

Definition

Chambers English Dictionary defines:

- **Etching** as "the act or art of etching or engraving: the impression from an etched plate"
- **To etch** as "to design on metal, glass etc. by eating out the lines with an acid; to eat away, corrode"

The above definition of etching, applied to the arts, is confusing, however, as it refers to the different techniques of etching and engraving (Chamberlain 1972) as one and the same process!

In terms of a production engineering process (Allen 2004), **etching** is better defined as: **a material removal process by accelerated, controlled corrosion, comprising a heterogeneous chemical reaction in which a liquid (or, more rarely, a gas) reacts with a solid material and oxidizes it to produce a soluble (or volatile gaseous) reaction product.**

Theory and Application

Etching as a Process Employed in Manufacturing and Production Technology

The “art” of etching (as defined in the Definition tag) was developed into a production process for the graphic arts, printing, and die-making industries, utilizing chemical etching and photoresist imaging to produce printing plates and dies by etching the surface of metals such as copper, zinc, and magnesium alloys. This process is commonly known as photoengraving (Wallis and Cannon 1969).

A further variation of this technique, developed in the late 1950s, led to etching completely through the metal plate to produce thin metal parts. This fabrication method is now known as photochemical machining or PCM (Allen 1986).

The above processes all use a protective photoresist layer to define the pattern to be etched. This provides a high-resolution patterning capability dependent on the wavelength of the electromagnetic radiation used for imaging: resolution being dependent on the frequency of the radiation used.

Other manufacturing techniques employ:

- Silkscreen imaging that allows coverage of large areas for (especially) decorative applications such as architectural panels
- A low-resolution maskant applied by spray, dipping, or flow-coating and cut by hand with a thin-bladed knife or cut by a robot-guided laser or water jet (Dini 1984). These processes are applied to large structures such as an aircraft fuselage or wing and aerospace launch vehicles. This technique is known as chemical milling (Harris 1976).

Some applications do not require a pattern etch but require an overall etch to thin the material or reduce weight in racing cars or even to taper a tall structure such as a yacht mast. These techniques are often applied to aluminum and titanium alloys, stainless steels, and even superalloys such as Rene 41 (Bellows 1977; Dini 1984).

In addition to the above processes, etching is also applied in the manufacture of microelectronic circuits where the materials etched are insulators, semiconductors, and polymers. Table 1 summarizes the combinations of etching technology available to the manufacturing engineer in terms of resolution required and size of component.

Objectives in Applying Etching Technology in Manufacturing

As etching technology employs chemical processing of materials, the question arises as to why traditional (mechanical) methods of machining are not successful in all cases. The answer lies in the ease of fabrication of the part and the associated costs of production. Conventional machining implies contact machining with a hard material cutting a softer material. However, if that material is extremely hard to machine, is thin enough to distort under the applied tool load, or is too large to be held in a machine tool fixture, then non-contact machining such as etching technology can be applied to give significant technical and economic advantages (Allen et al. 1989). A combination of imaging and etching technology can also provide a resolution capability exceeding that of conventional machining (Madou 2002).

Examples of successful applications of etching technology include:

- Production of nonstandard sheet metal gauge/thickness
- Texturing and removal of contact-machined directional surface finish and subsurface damage
- Weight reduction without compromising strength and/or rigidity
- Tapering of very long structures such as hollow tubes and solid rods
- Machining of large robust and delicate components
- Rapid production of thin, burr-free components where techniques such as stamping, wire-electrodischarge machining (WEDM), and laser beam machining (LBM) are costly

Error, Table 1 Etching techniques for production engineering

Etching technique	Patterning method	Materials	Typical area etched	Resolution
Photolithography	Photoresist	Insulators, semiconductors, and polymers	<0.5 m^2	Very high(nm–μm)
Photochemical machining (PCM)	Photoresist or silk screen	Conductors, polymers, glasses, and ceramics	mm^2–10 m^2	High (μm–mm)
Chemical milling	Maskant	Metals, mainly aluminum and titanium alloys	10–1,000 m^2	Medium (>100 μm)
Texturing, thinning, tapering, and weight reduction	–	Metals	m^2–1,000 m^2	Medium

due to complexity or batch size requirements (Allen et al. 1989)

- Production of extremely high-resolution, sub-micrometer features as required in the fabrication of microelectronic circuits, MEMS, MOEMS, micro- and nano-fluidic circuits, and Lab-on-a-Chip (LOC) devices (Madou 2002)

Materials

As **etching** is accelerated, controlled corrosion, the ease of etching a material is related to its corrosion resistance. The following materials may be etched:

- Insulators such as ceramics, glasses, photosensitive glasses, polymers, and plastics
- Semiconductors such as silicon, gallium arsenide, and other Group III–V semiconductors
- Conductors such as the metallic elements, metal alloys, and metallic glasses

Chemistry of Etching and Etching Mechanisms

Etching in solution comprises a heterogeneous chemical reaction in which an etchant reacts with a solid and oxidizes it to produce a soluble reaction product. It is important to note that if the reaction product were to be insoluble in the etchant, then the reaction would stop and etching would cease.

The rate of etching is controlled according to which is the slowest mechanism of the three reactions listed below:

- Transport, by diffusion, of the oxidizing etchant species to the solid surface
- Chemical reaction at the surface
- Transport, by diffusion, of the reaction product(s) away from the surface

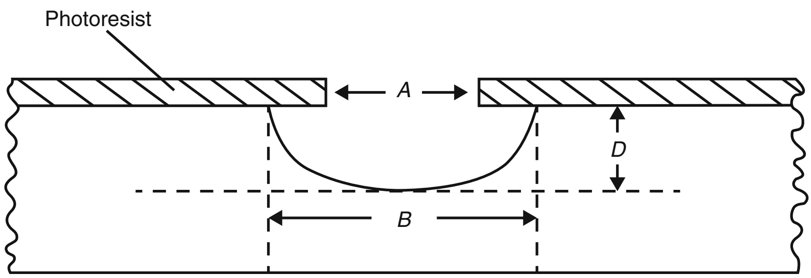
The rate of etching under diffusion-controlled kinetics is therefore increased by spraying the etchant onto the substrate as opposed to immersing it in a static bath of etchant. This is the reason that commercial PCM is carried out in a spray etching machine (Fig. 1) where etchant is sprayed from nozzles at typical pressures of 2–4 bar. Due to the size limitations of such machines, typically CHM applied to large parts is carried out in large tanks that can hold as much as 44,000 l of etchant (Dini 1984).

Isotropic and Anisotropic Etching

In etching technology, where a surface resist stencil is produced from photoresist imaging, screen stencil, or maskant cutting, chemical attack can occur into the body of the substrate, and once a sidewall has been formed, the etchant can attack beneath the stencil to form what is known as undercut (U) where U = 0.5 (B-A) (see Fig. 2). Normally the etch factor (D/U) is required to be as high as possible so that smaller holes can be etched into thicker materials.

The undercutting can be controlled when etching copper, zinc, and magnesium by the use of powderless etching additives. Such additives coat the sidewalls of etched cavities and protect them from further attack. However, the adhesion

Etching, Fig. 1 Spray etching machines (Courtesy of PrecisionMicro, Birmingham)



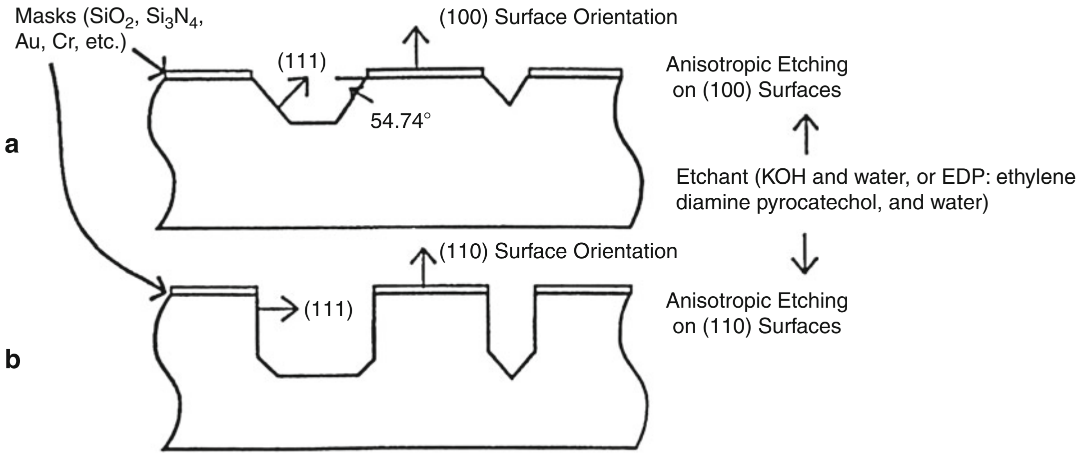
Etching, Fig. 2 Cross-section of etched material

is low and will not prevent depth etching so the etch factor is enhanced.

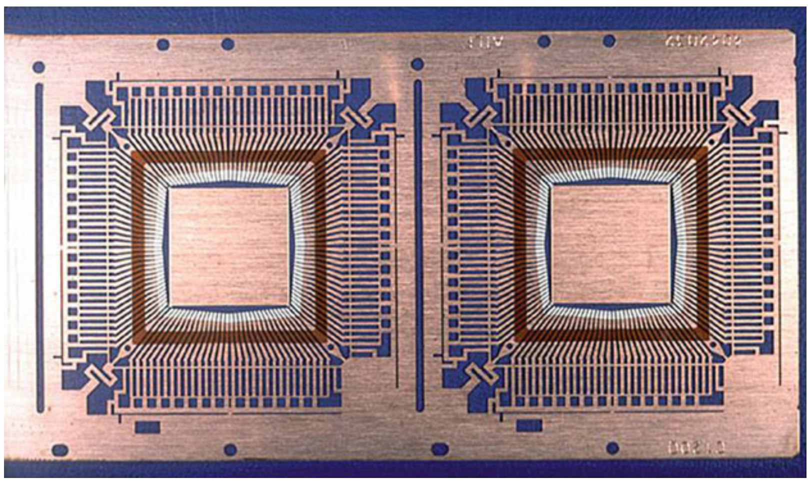
When etching single crystal materials such as (100) and (110) silicon, the lateral etching beneath the protective silicon dioxide or silicon nitride is effectively stopped by slow-etching (111) planes that produce well-defined geometries such as V-grooves and deep vertical slots (Allen 1981) as illustrated in Fig. 3.

Health and Safety Considerations of Etchants

As implied from the "Materials" section, the more corrosion-resistant materials will require more aggressive etchants than easy-to-corrode materials. Thus, ceramics and glasses are usually etched in etchants containing the toxic and hazardous etchant hydrofluoric acid (HF), certain polymers such as polyimide are etched in strong alkalis or concentrated acids (Harris 1976), but many engineering metallic materials are etched in dilute mineral acids such as nitric acid (e.g., magnesium and zinc) and the more benign oxidizing agent, aqueous ferric chloride ($FeCl_3$) solution. This latter etchant requires some free hydrochloric acid (HCl) to prevent hydrolysis of the $FeCl_3$ but is extremely versatile and therefore cost-effective in use. This etchant has been used to etch copper and its alloys, nickel alloys, steels, stainless steels, aluminum, and even molybdenum. Copper, as the high conductivity material of choice for use in printed circuit board fabrication, is also etched in cupric chloride and alkaline cupric ammonium chloride for ease of recycling the reaction products to reduce the environmental impact (Allen 1993).



Etching, Fig. 3 Anisotropic etch profiles in (**a**) (100) and (**b**) (110) silicon

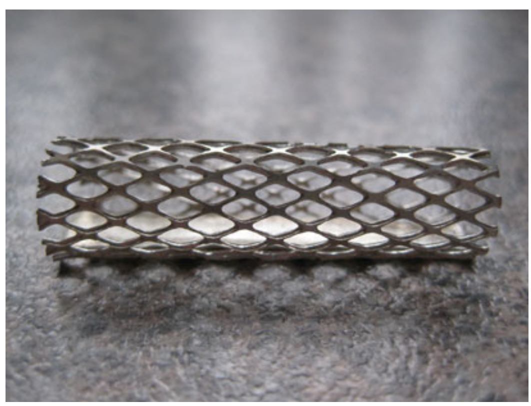


Etching, Fig. 4 Quad flat pack IC lead frames, width 60 mm

Applications

Applications of PCM are many and various and usually fabricated from thin materials <2.5 mm thick. Such products include:

- Grids, filters, meshes, and screens
- Levers, diaphragms, shims, gaskets, washers, springs, links, brackets, contacts, connectors, probes, heat sinks, IC lead frames, rotor and stator laminations, iris leaves, graticules, deposition masks, encoder discs, and jewelry
- Surface-etched rules, scales, clutch plates, bearings, hybrid circuit pack lids, enclosures, decorative goods, and components etched with logos, trademarks, part numbers, and instructions



Etching, Fig. 5 Prototype cylindrical magnesium stent

Copper alloy IC lead frames are illustrated in Fig. 4 and demonstrate the fact that complexity is not an issue for a non-contact machining technique. Figure 5 shows a prototype cylindrical magnesium stent etched and formed from a flat magnesium sheet (Allen et al. 2012).

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▶ Burr

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Eutectic Bonding

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Synonyms

Eutectic soldering

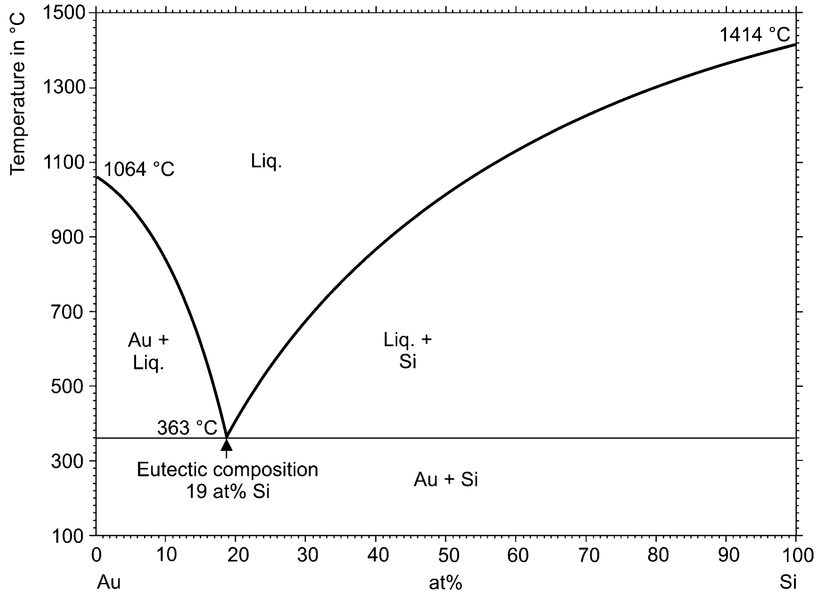
Definition

Eutectic bonding is a bonding method based on the melting of a metallic intermediate layer of eutectic alloy composition which is used for chip bonding and wafer bonding.

Theory and Application

Eutectic bonding (also called eutectic solder) is a low-temperature bonding method which is used in microelectronics manufacturing for chip bonding and to connect wafer with other wafers, glass substrates, or metal housings. In microsystem technology, the method also finds application in the generation of cavities and the production of MEMS. Here it is, however, compared to direct (fusion) bonding and anodic bonding rarely used (Dziuban 2006).

The method is based on the melting of a metallic intermediate layer of eutectic alloy composition which is applied between the substrates to be joined. This layer provides an electrically and heat conductive connection after the solidification. In the specific eutectic mixing



Eutectic Bonding, Fig. 1 Au–Si phase diagram (According to Okamoto and Massalski 1990)

ratio, the metal layer melts at a temperature which is much lower than the melting temperature of the pure alloy elements. This mixing ratio is also characterized by the fact that the physical state at the melting temperature changes directly from solid to liquid, without passing through a two-phase condition.

The alloy of the metallic intermediate layer is in many applications based on a composition of silicon (Si) with gold (Au) or aluminum (Al). Furthermore, there are other alloy compositions, which are each associated with a specific melting temperature. In a phase diagram, the melt temperature of the phases as a function of the concentration of alloying elements as well as the concentration ratios is plotted. Figure 1 shows the Au-Si alloy system with the corresponding phase diagram.

In the example of Au–Si, the eutectic composition lies at a mixing ratio of 81 at% (97 wt%) Au and 19 at% (3 wt%) of Si. The corresponding melting temperature of 363 °C represents the global minimum of the melting temperature of this alloy system and is much lower than the melting temperature in the amount of 1,064 °C for pure gold or 1,414 °C for pure silicon.

A common application of the method is based on the vapor deposition of thin gold layers on Si substrates. During the process, a diffusion of silicon atoms in the gold layer occurs which generates an eutectic alloy ratio. Subsequently, the intermediate layer melts and then solidifies to form a conductive connection (Dziuban 2006).

If the bonding process is carried out at a higher than the eutectic melting temperature, further diffusion of atoms occurs in the region of the metallic intermediate layer and consequently leads to a separation phenomena of the alloy. This in turn leads to an increase in the melting temperature and thereby to a solidification of the alloy at higher temperatures (Dziuban 2006). In addition, the solidification is no longer in the form of a eutectic mixture of homogeneous composition, but there is solid solution precipitation from the melt. These form fibrous structures at the bonding site, which lead to uneven formations and stress conditions (Wolffenbuttel and Wise 1994). These precipitates can be reduced by an adequate combination of process temperature and process time (Dziuban 2006).

Procedural Steps

Eutectic bonding of wafers consists mainly of the three following steps:

Preparation of Surface for Bonding

A clean surface of wafers is required for the eutectic bonding process, because the wafers must adhere to each other firmly. To evaluate the surface cleanness, the wetting angle of a water drop located on the surface can be used (Dziuban 2006). The method of cleaning and drying of wafers determines the state of the surface. There is no big difference between the method of cleaning for silicon and glass surface.

For the silicon wafer, the bonding procedure is very limited because of the oxide presence. The gold indicates a poor wettability on an oxide surface, which results in a poor adhesion of the eutectic bond. This problem should be solved to accomplish the eutectic bonding process successfully. One possibility is that the oxide can be broken through rubbing the silicon wafers during the attachment process. A second technique is removal of the oxide prior to bonding. Another method is to use an additional thin intermediate metal film that adheres well to the oxide. Commonly used suitable metals for the Au-Si eutectic bonding are titanium (Ti) and chromium (Cr), which is consequently as Si–SiO_2–Ti–Au or Si–SiO_2–Cr–Au. The silicon diffuses into this intermediate metal and subsequently the oxide will be broken up (Wolffenbuttel 1997).

Bonding Process

It is commonly recommended that the bonding should be carried out immediately after cleaning and activation of wafers, within 3 h (Dziuban 2006), so that the oxide regeneration can be avoided.

The substrate is fixed on a heated stage, on which the silicon wafer will be bonded. At the beginning, a sub-μ layer of gold is sputtered on the substrate. It is heated to a temperature, a little higher than the eutectic temperature of 363 °C (Dziuban 2006), and a specific pressure is applied. As soon as the layer is in atomic contact with the silicon, the reaction starts. Through the diffusion of the gold atoms into silicon, an Au–Si alloy is formed. As the eutectic composition is reached, the Au–Si alloy starts to melt, coming into a liquid phase. This liquid phase accelerates the diffusion process of the gold atoms into the silicon.

It is recommended to implement a short period of the bonding process at 365 °C for about 10 min because the potential appearance of texturization at the bonded surface at a higher temperature should be avoided (Dziuban 2006).

However, for the bonding procedure, a higher temperature than the eutectic temperature is usually preferred, so that the bonding strength of the eutectic bond is enhanced. In spite of the texturization appearance under a higher temperature, the bonding process is normally implemented in practice at 390 °C, so that the heat between the wafers and alloy is successfully transferred. Only in this way, a reliable bonding process will be accomplished.

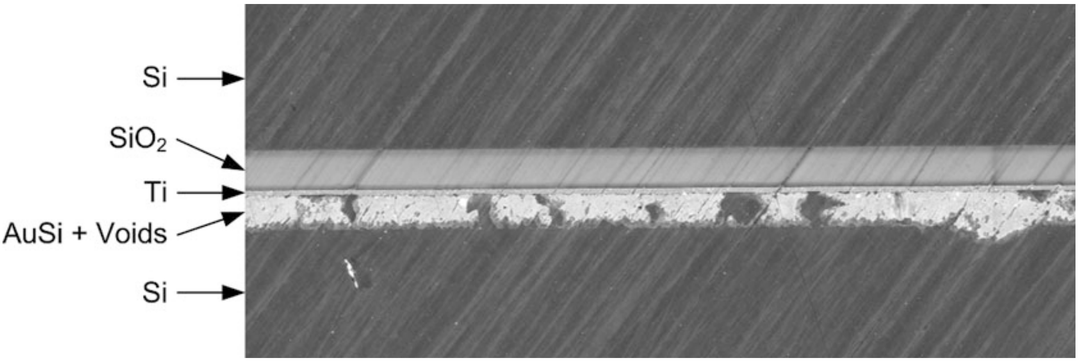
Annealing Process

After bonding process, annealing is proceeded. At the eutectic point, the liquid phase maintains gold diffusion into the silicon until the saturation composition is reached. During this process, the ratio of gold and silicon in the eutectic Au-Si alloy has been changed; thus, the alloy composition will be solidified. This also happens when the temperature decreases below the eutectic point. In either case, the solidified composition will be annealed and this should be performed under an inert gas flow, such as nitrogen.

Figure 2 shows a cross section of bonded wafers after an eutectic bonding process. An intermediate layer of gold (Au) is utilized for bonding of two silicon wafers (Si), one covered with oxide (SiO_2) and a diffusion barrier (Ti), the other one after oxide removal prior to bonding. During the bonding process, the eutectic alloy forms and local voids occur within the AuSi layer.

Application

Eutectic bonding has been mainly applied in microelectronics technology. It is used to stack silicon dies, to bond silicon wafers, and it has been adopted in the packaging of silicon



Eutectic Bonding, Fig. 2 Cross section SEM image of wafer interface after oxide removal at bottom wafer and subsequent eutectic bonding; Si–SiO_2–Ti–AuSi–Si (Fraunhofer ENAS)

Eutectic Bonding, Fig. 3 High speed dual head die bonder (*Amicra*)

microelectronics and the production of MEMS. Figure 3 shows a commonly used die bonding machine.

It has been more and more important to develop the integration technologies like packaging at different levels, combining MEMS with integrated circuits and realizing three-dimensional packaged devices (Baum et al. 2010).

Low-temperature aluminum-germanium (Al–Ge) eutectic bonding at a low temperature of 435 °C has been investigated for monolithic three-dimensional integrated circuit (3DIC) applications (Crnogorac et al. 2009).

Development in area of RF-MEMS for wireless communication is recently strong required. Thus, a wafer level eutectic bonding technology with Au–Sn at the temperature of 300 °C has been applied for RF-MEMS due to the advantage of its low temperature (Wang et al. 2006). Also an Au–Si eutectic wafer bonding technology has been applied for reproducible hermetic/vacuum packaging required for RF-MEMS (Mitchell et al. 2006).

Advantages and Disadvantages

Advantages:

- High mechanical strength.
- High thermal and chemical resistance.
- Good electrical conductivity.
- Low requirement on surface quality and planarity.
- Technologically compatible with IC processes (Dziuban 2006).
- Low temperature of process avoids destruction of metallization (Dziuban 2006).

Disadvantages:

- Demand of additional materials for oxide adhesion respectively oxide removal.
- Different coefficients of thermal expansion.
- Stability of Si-Au-Si bonding might vary over time and vacuum-tight connections might fail (Dziuban 2006).
- Reduced lifetime of charge carriers in silicon under the influence of gold (Dziuban 2006).

Cross-References

▶ Bonding
▶ Bonding Materials

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Eutectic Soldering

▶ Eutectic Bonding

Exactitude

▶ Precision

Exactness

▶ Precision

Expenditure

▶ Cost

Expense

▶ Cost

Expert Systems

▶ Knowledge-Based System

Extension

▶ Stretching

Extreme Precision

▶ Ultraprecision

Extrusion

▶ Bar Extrusion

Extrusion of Sections

▶ Bar Extrusion