ELECTRICAL ENGINEERING TECHNOLOGY

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Chapter I: *Introduction to Fabrication Technology*

I.1. What is Technology?

The word ***technology*** comes from the Greek ï Űӳɢɜɖ (techne), which means "art, skill, craft, cunning of hand"; and ï ɚɞɔɗŬ (logia) which refers to the making, modification, usage, and knowledge of tools, machines, techniques, crafts, systems, and methods of organization, in order to solve a problem, improve a pre-existing solution to a problem, achieve a goal, handle an applied input/output relation or perform a specific function. It can also refer to the collection of such tools, including machinery, modifications, arrangements and procedures.

Technologies give the ability to control and adapt our natural environment in order to ensure better living conditions. The first use of technology leads to natural resources conversion into simple tools. The prehistorically discovery of the ability to control fire increased the available sources of food; the invention of the wheel helped humans in travelling in and controlling their environment. Recent technological developments, including the printing press, the telephone and the Internet, have lessened physical barriers to communication and allowed humans to interact freely on a global scale. However, not all technology has been used for peaceful purposes; the development of weapons of ever-increasing destructive power has progressed throughout history, from clubs to nuclear weapons.

Technology has affected society and its surroundings in a variety of ways. In many societies, technology has helped develop more advanced economies (including today's global economy) and has allowed the rise of a leisure class. But, many technological processes produce unwanted effects such as: pollution and deplete natural resources, to the detriment of Earth's environment.

Various implementations of technology influence the values of a society and new technology often raises new ethical questions. Examples include the rise of the notion of *efficiency* in terms of human productivity, a term originally applied only to machines, and the challenge of traditional norms.

Philosophical debates have arisen over the present and future use of technology in society, with disagreements over whether technology improves the human condition or worsens it.

Technology can be most broadly defined as the entities, both material and immaterial, created by the application of mental and physical effort in order to achieve some value. In this usage, technology refers to tools and machines that may be used to solve real-world problems. It is a far-reaching term that may include simple tools or more complex machines, as well as virtual means such as computer software and business methods.

The word ***technology*** can also be used to refer to a collection of techniques. In this context, it is the current state of humanity's knowledge of how to combine resources to produce desired products, to solve problems, fulfill or satisfies needs; it includes technical methods, skills, processes, techniques, tools and raw materials. When combined with another term, such as ñmedical technologyò, ñinformation technologyò or ñspace technologyò, it refers to the state of the respective field's knowledge and tools. "State-of-the-art technology" refers to the high technology available to humanity in any field.

The distinction between *science*, *engineering* and *technology* is not always clear.

Science is the reasoned investigation or study of phenomena, aimed at discovering enduring principles among elements of the phenomenal world by employing formal techniques such as the scientific method.

Technologies are not usually exclusively products of science, because they have to satisfy requirements such as *utility*, *usability* and *safety*.

Engineering is the goal-oriented process of designing and making tools and systems to exploit natural phenomena for practical human means, often (but not always) using results and techniques from science.

The development of technology may draw upon many fields of knowledge, including scientific, engineering, mathematical, linguistic, and historical knowledge, to achieve some practical result.

Technology is often a consequence of science and engineering ï although technology as a human activity precedes the two fields. For example, science might study the flow of electrons in electrical conductors, by using already-existing tools and knowledge. This new-found knowledge may then be used by engineers to create new tools and machines, such as semiconductors, computers, and other forms of advanced technology. In this sense, scientists and engineers may both be considered technologists; the three fields are often considered as one for the purposes of research and reference.

As a science, technology can be divided into two branches:

- theoretical technology,
- applied technology.

Theoretical technology deals with theories and theoretical models for developing, synthesizing and improving creation processes or knowledge.

Applied technology can be subdivided into four different categories, based on the aimed goal:

- *fabrication technology* – refers to products manufacturing,
- *exploiting technology* – refers to efficiency using of the existing goods and knowledge,
- *maintenance technology – refers to maintaining the working state of all means of production,*
- *repairing and reconditioning technology – refers to restoring or replacing the damaged or non-working products or parts.*

I.2. Defining Technology Systems

Technology systems refer mainly to material objects used in production process, such as tools, devices, machines, hardware or utensils, but can also encompass broader themes, including systems, methods of organization, and techniques. Associated to technology systems is also used the term ñ***equipment***ò which defines the ensemble off all component parts of a system.

Main equipment categories used in fabrication process are next briefly discussed.

Machine tools: material-removal machines are commonly referred to as ñ*machine tools*ò. Such machines are utilized extensively in the manufacturing industry for a variety of material-removal tasks, ranging from simple hole making (drilling or boring) to producing complex contoured surfaces on rotational or prismatic parts (turning and milling). Metal cutting and forming has been a major manufacturing challenge since the early stage of industrialization. Although modern machine tools and presses tend to be similar to their early versions, current machines are more powerful and effective. With the introduction of automatic control technologies, these machines became easier to utilize in the production of complex geometry work pieces, while providing excellent repeatability. Due to the worldwide extensive utilization of machine tools by small, medium and large manufacturing enterprises and the longevity of these machines, it is impossible to tell with certainty their current number.

Industrial robots: a manipulating industrial robot is defined by the International Organization for Standardization (ISO) as an automatically controlled, reprogrammable, multi-purpose, manipulative machine with several degrees of freedom, which may be either fixed in place or mobile for use in industrial application. This definition excludes automated guided vehicles and dedicated automatic assembly machines. Their initial utilization on factory floors were for simple repetitive tasks in either handling bulky and heavy work pieces or heavy welding guns in point-to-point motion. Their application spectrum was later widened to include arc welding and pray painting in continuous-path motion. Today, industrial robots can be found in many high-precision and high-speed applications. However, still, due to the lack of effective sensors, industrial robots cannot be utilized to their full capacity in an integrated sense with other production machines. They are mostly restricted to repetitive tasks, whose pick and place locations or trajectories are a priori known; they are not robust to positional deviations of work piece locations.

Mechanisms: are special devices designed to transform input forces and movement into a desired set of output forces and movement. Mechanisms generally consist of moving components such as gears and gear trains, belt and chain drives, cam and follower mechanisms, and linkages as well as friction devices such as brakes and clutches, and structural components such as the frame, fasteners, bearings, springs, lubricants and seals, as well as a variety of specialized machine elements such as splines, pins and keys.

*Apparatus***:** a group or system of organs that collectively perform a specific function or process; the technical equipment or machinery needed for a particular activity or purpose.

Instruments: different devices for recording, measuring, or controlling, especially such a device functioning as part of a control system.

Device: a contrivance or an invention serving a particular purpose used to perform one or more relatively simple tasks; usually a constructed tool, but may refer also to a simple machine or a gadget.

I.3. Production Process

The production process is concerned with transforming a range of inputs into those outputs that are required by the market. This involves two main sets of resources: the transforming resources, and the transformed resources.

The transforming resources include the buildings, machinery, computers, and people that carry out the transforming processes.

The transformed resources are the raw materials and components that are transformed into end products.

Any production process involves a series of links in a *production chain*. At each stage value is added in the course of production. Adding value involves making a product more desirable to a consumer so that they will pay more for it. Adding value therefore is not just about manufacturing, but includes the marketing process, including advertising, promotion and distribution that make the final product more desirable.

It is very important for enterprises to identify the processes that add value, so that they can enhance these processes to the ongoing benefit of the business.

There are three main types of processes:

- *job production,*
- *batch production,*
- *flow production.*

Job production

Job or ñ*make complete*ò production is the creation of single items by either one operative or a team. It is possible for a number of identical units to be produced in parallel under job production. Smaller projects can also be seen as a form of job production.

Job production is unique in the fact that the project is considered to be a single operation, which requires the complete attention of the operative before he or she passes on to the next job.

The benefits of job production are:

- the job is a unique product, which exactly matches the requirements of the customer, often from as early as the design stage. It will therefore tend to be specific to a customer's order and not in anticipation of a sale. For example, someone building an electric customized car will first discuss with the customer the desired feature. A detailed documentation would then be produced and once itĝs finished, the production process will start. The finished product will then be inspected by the customer who will pay for the unique product.

- as the work is concentrated on a specific unit, supervision and inspection of work are relatively simple.

- specifications for the job can change during the course of production depending upon the customer's inspection to meet his or her changing needs.

- working on a single unit job, coping with a variety of tasks and being part of a small team working towards the same aim would provide employees with a greater level of satisfaction.

Batch production

The term *batch* refers to a specific group of components, which go through a production process together. As one batch finishes, the next one starts. For example, for a period of time, a specific machine tool produces only one electric motor component type, then for another time period it produces a different electric motor component and so on. All electric motor parts will then go forward to the final assembly.

Batches are continually processed through each machine before moving on to the next operation. This method is sometimes referred to as ñ*intermittent*ò production as different job types are held as work-in-progress between the various stages of production.

The benefits of batch production are:

- it is particularly suitable for a wide range of almost similar goods, which can use the same machinery on different settings.

- it reduces the range of machinery needed and the need for a flexible workforce.

- units can respond quickly to customer orders by moving buffer stocks of work-in-progress or partly completed products through the final production stages.

- it makes possible economies of scale in techniques of production, bulk purchasing and areas of organization.

- it provides a better information service for management.

Flow production

Flow production is a continuous process of parts and sub-assemblies passing on from one stage to another until completion.

Units are worked upon in each operation and then passed straight on to the next work stage without waiting for the batch to be completed. To make sure that the production line can work smoothly each operation must be of standard lengths and there should be no movements or leakages from the line.

For flow production to be successful there needs to be a continuity of demand. If demand varied, this could lead to a constant *overstocking* of finished goods.

Although with modern robotics it is possible to create variations in products being produced through continuous flow techniques, typically such products will be relatively *standardized*.

Achieving a smooth flow of production requires considerable pre-production planning to make sure that raw materials are purchased and delivered just-in-time, that sufficient labor is employed and there is continuous attention to quality throughout the production process.

The benefits of flow production are:

- ease of using just-in-time techniques to eliminate waste and minimize costs;

- labor and other production costs will be reduced through detailed planning and the use of robotics and automation;

- deviations in the line can be quickly spotted through ongoing quality control techniques;

- as there is no rest between operations, work-in-progress levels can be kept low;

- the need for storage space is minimal;

- the physical handling of items is minimal;

- investment in raw materials and parts are quickly converted into sales
- control is easy.

I.4. Computing and IT Technologies

Even from the early stages of computer development, both hardware and software, computing technologies were used for computer-aided engineering (CAE). With the introduction of computer-aided design (CAD) software and smart graphic terminals, engineering could easily develop the geometric models of products, which they wanted to analyze via existing engineering analysis software such as ANSYS, CATIA, CEDRAT, etc.

Another major impact of computing technology was, naturally, in automatic and intelligent control of production machines, starting with the first concept of a numerical controlled (NC) industrial application, to the present distributed computer numerical control (DCNC) systems, in which machine tools are networked and connected to a central computer.

With the late extraordinary evolution of the World Wide Web (WWW) as a commercial vehicle, many manufacturing companies started the transformation of the whole industry into *information technology* (IT)-based supply chains (spanning from customers at one end to component suppliers at the other). Today, highly competitive markets force manufacturing enterprises to network; they must place the customer at the center of their business while continuing to improve on their relationships with suppliers. This transformation will, however, only come easy to companies that spent the past two decades trying to achieve manufacturing flexibility via advanced technologies (for design, production, and overall integration of knowledge sharing) and implementation of quality-control measures.

IT-based manufacturing requires rapid response to meet personalized customer demands. A common trend for manufacturing enterprises is to establish reliable interconnected supply chains by pursuing connectivity and coordination. A critical factor to the success of these companies will be the managing of (almost instantaneous) shared information within the company through intranets and with the outside world through extranets. The task becomes increasingly more difficult with large product-variation offerings.

Information sharing is an important tool in reducing uncertainties in forecasting and in thus providing manufacturers with accurate production orders. In the next decade, we should move toward total collaboration between the companies within a supply chain, as opposed to current underutilization of the web through simple information exchange on demand via extranets. True collaboration requires the real-time sharing of operational information between two supply-chain partners, in which each has a window to the otherôs latest operational status. In a retail market supply environment this could involve individual suppliers having real-time knowledge of inventories as well as sales patterns and make autonomous decisions on when and what quantity to resupply. Similarly, in supplying assemblers, component manufacturers can access the formersô production plans and shop status to decide on their orders and timing.

Whether the web has been the missing link in the advancement of manufacturing beyond the utilization of the latest autonomous technologies will be answered in the upcoming decade by fabrication strategy analysts. In the meantime, enterprises should endeavor to achieve high productivity and offer their employees intellectually challenging working environments via the utilization of what we know now as opposed to reluctantly waiting for the future to arrive.

I.5. Fabrication Technology Management

Technology management can be defined as the integrated planning, design, optimization, operation and control of technological products, processes and services. A better definition would be the management of the use of technology for human advantage.

The role of the technology management function in an organization is to understand the value of certain technology for the organization. Continuous development of technology is valuable as long as there is a value for the customer and therefore the technology management function in an organization should be able to argue when to invest on technology development and when to withdraw.

The Association of Technology, Management, and Applied Engineering defines *technology management* as the field concerned with the supervision of personnel across the technical spectrum and a wide variety of complex technological systems. Technology management programs typically include instruction in production and operations management, project management, computer applications, quality control, safety and health issues, statistics, and general management principles.

Perhaps the most authoritative input to our understanding of technology is the diffusion of innovations theory developed in the first half of the twentieth century. It suggests that all innovations follow a similar diffusion pattern - best known today in the form of an "s" curve though originally based upon the concept of a standard distribution of adopters. In broad terms the "s" curve suggests four phases of a technology life cycle - emerging, growth, mature and aging.

These four phases are coupled to increasing levels of acceptance of an innovation or, in our case a new technology. In recent times for many technologies an inverse curve - which corresponds to a declining cost per unit - has been postulated. This may not prove to be universally true though for information technology where much of the cost is in the initial phase it has been a reasonable expectation.

It has been said many times, especially during the early 1980ŝ, that a nation can prosper without a manufacturing base and survive solely on its service industry. Fortunately, this opinion was soundly rejected during the 1990ŝ, and manufacturing once again enjoys the close attention of engineers, managers, and academics. It is now agreed that an enterprise must have a competitive fabrication strategy, setting a clear vision for the company and a set of achievable objectives.

A manufacturing strategy must deal with a variety of issues from operational to tactical to strategic levels. These include decisions on the level of vertical integration, facilities and capacity, technology and workforce, and of course organizational structure.

The successful enterprise of today is normally divided into a number of business units for effective and streamlined decision making for the successful launch of products and their production management as they reach maturity and eventually the end of life. A business unit is expected continually and semi-independently to make decisions on marketing and sales, research and development, procurement, manufacturing and support, and financial matters. Naturally, a fabrication strategy must be robust and evolve concurrently with the product.

As the history of manufacturing shows us, companies will have to make difficult decisions during their lives (which can be as short as a few years if managed unsuccessfully) in regard to remaining competitive via marketing efforts or innovative designs. As one would expect, innovation requires investment (time and capital): it is risky and return on investment can span several years. Thus the majority of products introduced into the market are only marginally different from their competitors and rarely survive beyond an initial period.

No manufacturing enterprise can afford the ultra flexibility continually to introduce new and innovative products into the market place. Most, instead, only devote limited resources to risky endeavors. A successful manufacturing company must strike a balance between design innovation and process innovation. The enterprise must maintain a niche and a dominant product line, in which incremental improvements must be compatible with existing manufacturing capability, i.e., fit within the operational flexibility of the plant.

It is also expected that a portion of profits and cost reductions achieved via process innovations on mature product lines today, to be invested in the tomorrowôs innovative products.

I.6. Fabrication Flexibility

Fabrication flexibility has been described as the ability of an enterprise to cope with environmental uncertainties: óóupstreamôô uncertainties, such as production problems (e.g., machine failures and process-quality problems) and supplier-delivery problems, as well as óódownstreamôô uncertainties due to customer-demand volatility and competitorsô behavior.

Rapid technological shifts, declining product life cycles, greater customization and increased globalization have all put increased pressure on manufacturing companies significantly to increase their flexibility.

Thus a competitive company must today have the ability to respond to customer and market demands in a timely and profitable manner.

Manufacturing flexibility is a continuous medium spanning from operational to strategic flexibilities on each end of the spectrum: *operational flexibility* (equipment versatility in terms of reconfigurability and reprogrammability), *tactical flexibility* (mix, volume and product-modification robustness), and *strategic flexibility* (new product introduction ability).

One can rarely achieve strategic flexibility without having already achieved the previous two. However, as widely discussed in the literature, tactical flexibility can be facilitated through in-house (advanced-technology-based) flexible manufacturing systems or by outsourcing, namely, through the development of an effective supply chain.

It has been argued that as an alternative to a vertically integrated manufacturing company, strategic outsourcing can be utilized to reduce uncertainties and thus to build competitive advantage without capital investment. As has been the case for several decades in Germany and Japan, early supplier involvement in product engineering allows sharing of ideas and technology, for product as well as process improvements. Naturally, with the ever-increasing effectiveness of current communication technologies and transportation means, supply chains do not have to be local or domestic. Globalization in outsourcing is here to stay.

I.7. Manufacturing and Sustainability

Sustainability is usually defined as ñmeeting the needs of the present without compromising the ability of future generations to meet their own needsò. The sustainability of a manufacturer is measured by the effect of its operations and its products throughout their lifecycle. Issues related to sourcing (where applicable), downstream impact, and strategies are addressed below in the context of the most pressing environmental matters of the day.

Sustainable manufacturing is defined as the creation of manufactured products that use processes that are non-polluting, conserve energy and natural resources and are economically sound and safe for employees, communities, and consumers.

Manufacturers use *raw materials* as inputs and transform them into finished goods. Materials like wood, copper, and steel were once cheap and plentiful, but are growing ever more expensive and harder to find. Cost and availability are likely to worsen as rapid growth in newly industrializing countries consumes natural resources faster than they can be replenished or substitutes found.

The harvest and extraction of natural materials can cause substantial environmental harm, especially as supplies dwindle and resource recovery becomes more invasive. Industrial materials often emit pollutants as byproducts of their production process. A lifecycle assessment of a manufactured good will include the environmental impact of the productôs material inputs as well as the production process. The lifetime impact of a product may vary significantly based on the materials selection and on the amount of materials consumed.

Water is also use as an input in the production process, and some industries are particularly water-intensive. Only a tiny fraction of the planetôs water is fit for human consumption, and the amount is shrinking fast as aquifers are overdrawn, chemicals leach into groundwater, and climate change shrinks lakes and reservoirs. Seasonal and crisis-related shortages are common in some regions and likely to increase in coming years. At-risk communities are increasing their reliance on recycled water to meet the non-potable needs of residents and businesses. As humans, wildlife, agricultural and commercial interests increasingly compete for access to clean water, the price of water is steadily climbing. Many observers predict that future wars will be fought over water.

Fabrication processes that use water frequently emit wastewater containing chemicals, suspended solids and other impurities. Depending on its composition, the wastewater may be subject to local health regulations and require expensive treatment and remediation.

Virtually all manufacturing processes use *energy*. Regardless of type and source, energy prices have escalated over the past 50 years. Unless manufacturers have invested in energy efficiency, energy costs now represent a larger share of operating expenses than ever before, with no end in sight. The electric grid infrastructure is aging, inadequate and vulnerable to outages in many parts of the world. On-site power generation and alternative sources may be more reliable in some instances than power purchased from a central utility.

Worldwide, most energy is produced by the combustion of carbon-based fossil fuels such as coal, gas and oil. The resulting greenhouse gas emissions are a major cause of global warming and increasingly subject to regulation. Large emitters, including businesses that consume large amounts of electricity and natural gas, are or will soon be required to monitor and report, then limit their output. The more carbon-based energy a manufacturer uses in its operations, the more affected it will be by reporting requirements, emission limits and carbon taxes. Its higher operating expenses will be reflected in its higher cost of goods.

Manufacturers also need to consider the energy cost and related emissions of packaging and shipping their raw materials, component parts, and finished goods. If products are made or assembled in developing countries for sale in industrialized regions, the overall energy footprint may skew heavily toward transportation.

Purchasers also care about the energy consumption, financial and environmental impacts of a product. If machinery or a consumer product is designed to run on electricity or a carbon-based fuel like oil, coal or natural gas, its total cost of ownership will increase proportionally with its energy consumption. The energy efficiency of a product is a newly important feature and competitive differentiator.

The *waste* problem has become, lately, a worldwide international problem. Landfills are at capacity and difficult to site; decomposing trash emits greenhouse gases more potent than carbon dioxide, and escaping chemicals can contaminate the soil and water supply. Incinerators are under pressure to close because they emit benzene and chlorine, carcinogens that endanger human health and the environment. In response to the growing acknowledgement that there is no place on earth to throw things ñawayò more than 50 government entities worldwide have adopted a goal of zero waste.

Pollution is another form of waste, one with a clearly negative impact on the environment. Particulates, gas emissions and the solids found in wastewater, sludge and ash can all cause significant harm to humans and habitat. Pollution mitigation measures are required under local, state and/or federal regulations, and compliance measures can be expensive. Failure to comply with regulations can lead to steep penalties, possible civil and criminal litigation and consumer boycotts.

Manufacturers must consider the waste produced by their products as well as their operations. Products that generate unwanted byproducts will be more costly and troublesome to their purchasers than ones that operate more efficiently. Products covered by extended producer responsibility policies, either mandatory or voluntary, will impose higher costs and hassles on manufacturers if they are not designed for efficient disassembly and resource recovery.

The increasing importance of environmental issues to manufacturers poses risks and offers opportunities. The following section briefly connects the opportunities to the business challenges commonly faced by producers.

- *Profitability*

Using less energy in the production process lowers overhead and product costs. Companies that lower their cost of goods and operations have more money to invest in upgrading plant or equipment or capital improvements, all of which can contribute to greater competitiveness and long-term success.

Using fewer materials also cuts costs. Switching to more sustainable materials may or may not reduce costs at the front end, but will likely reduce waste, emissions and pollution, and perhaps avoid shortages or price increases for the less-sustainable material.

Companies that use natural resources wisely and take positive steps to lower their environmental impact are more successful in attracting and retaining loyal customers and staff.

- *Competition*

Sustainability is still a differentiator, but not for long, it is quickly becoming an expected part of doing business in the global economy.

Customers claim in surveys that they are willing to pay more for a safe, healthy, green product. Recent concerns about the presence of dangerous chemicals and materials in imported goods give domestic manufacturers a chance to regain market share for some types of consumer goods.

Products that use minimal energy and water during their useful life will cost less to own and operate than less resource-efficient alternatives.

- *Compliance and Managing Risk*

Regulatory pressures will continue to increase and expand to cover materials and products whose cumulative environmental impact is deemed unacceptable (such as non-biodegradable plastic).

Pro-actively reducing the carbon and chemical footprint of a business now can avert or minimize negative regulatory impacts later.

A sustainable approach reduces risks at every stage of business, leaving businesses less exposed to the possibility of materials shortages, energy price increases, higher fees for waste disposal and pollution abatement, liability and unwelcome shareholder actions.

- *Market Opportunities/Growth*

Major corporations and public agencies are increasingly demanding emissions reporting and mitigation plans from their supply chain partners. Suppliers who can show an understanding of the issues and progress toward goals will win business away from those that do not.

Earning a valued third party certification designation puts products on the short list for businesses and government agencies that have implemented an environmentally preferable purchasing policy.

Sustainability challenges are spurring the need for new solutions. Manufacturers that can add or extend an existing product line to meet the challenges have huge market opportunity.

Manufacturers can lower their expenses by improving the resource efficiency of their operations in the front office, back office and factory. Opportunities for growth will come from improvements in product design.

Improving energy efficiency in offices and factories is usually a relatively easy and cost-effective way to enhance environmental performance. *Energy audits* (often provided free of charge by the local power utility) consistently find savings opportunities in lighting and HVAC systems. Many times, capital improvements such as adding insulation, upgrading windows and installing variable frequency drive pumps offer quick paybacks as well.

Beyond energy efficiency, the following kinds of projects are relatively simple to implement and offer an attractive return on investment:

The fabrication process is resource-intensive by nature. Common sense dictates that using less energy and water during production and reducing materials waste will help a business lower its costs and operational footprint. In reality, however, some producers may be reluctant to modify familiar processes based on the chance that they can create the same quality product with fewer resources. The costs of downtime, retooling, worker retraining, safety and performance testing are well known to manufacturers; the benefits of a greener operation are theoretical until proven.

Two factors reduce the risk of updating a production process to improve its sustainability: one is using a proven methodology and the other, a proven technology.

But the greatest environmental impact of some products comes not during their manufacture, but during their useful life. Industrial equipment, consumer electronics, cell phones (anything with an on/off switch) may consume many times more energy in a year than was consumed during its production or embedded in its raw materials. In other cases, the choice of materials may be the most critical environmental factor associated with a product. Both issues are of growing importance to customers, supply chain partners and regulators. Products with low eco-footprints offer a lower total cost of ownership, less chance of liability and fewer regulatory hurdles for producers and buyers alike. In short, such products are more competitive than their traditional counterparts are and may fuel a manufacturerọs growth.

Chapter II: *Product Design*

The Accreditation Board for Engineering and Technology (ABET) considers product design as an iterative decision-making process, in which natural sciences, mathematics, and applied sciences (engineering) are applied to meet a stated objective in an optimal manner. A diagram of this process is presented in Fig.1.

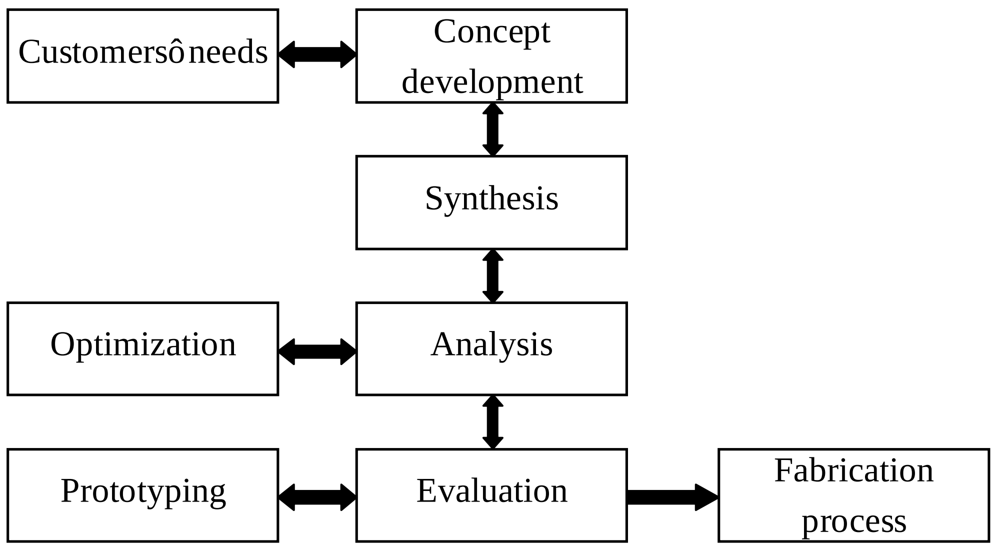


Fig.1: Product design process

However, product design process is not such a neat sequential process as is shown into the above diagram. Today, product development teams have multidisciplinary members who concurrently work on several aspects of design, without being totally restricted by any sequential approach.

In this chapter, *conceptual design* will be discussed as the first step in the engineering design process. Customer-needs evaluation, concept development (including industrial design), and identification of a viable product architecture are the three primary phases of this stage of design.

Several engineering design methodologies will also be presented as common techniques utilized in the synthesis stage of the design process. They include the axiomatic design methodology developed by N. Suh (M.I.T.), the Taguchi method for parameter design, as well as the group-technology (GT)-

based approach, originally developed in Europe in the first half of the 20th century, for efficient engineering data management.

Computer-aided solid modeling techniques such as constructive solid geometry and boundary representation methods will next be presented as necessary tools for downstream engineering analysis applications.

Feature-based computer-aided design will also be discussed in this chapter along with the computer-aided engineering (CAE) analysis and prototyping of products in “virtual space”. Finite-element analysis and parameter optimization will be used for choosing the “best” design.

II.1. Conceptual Design

Product design starts with a need directly communicated by the customer or with an innovative idea developed by a research team that would lead to an incremental improvement on the state of the art, or to a totally new product. Even if there have been only a very few inventions in the 20th century, most products have been incrementally innovated.

II.1.1. Concurrent Engineering

The need for accelerated product launch in the face of significantly shortened product life cycles, especially in the communications and computing industries, has forced today’s manufacturing companies to assemble multidisciplinary product design teams and ask them for concurrent input into the design process.

Concurrent Engineering (CE) is a systematic approach to the integrated (concurrent) design of products and their manufacturing and support process. The product development team must consider all elements of the product life-cycle from the outset, including safety, quality, cost and disposal. Computer-aided design and engineering (CAD/CAE) tools are usually used.

It has been advocated that CE could benefit from moving away from a function-based manufacturing structure toward a team-based approach. Lately, however, companies have been adopting a hybrid approach: they maintain product-based business units as well as function units that comprise highly skilled people who work (and help) across product business units.

In this context, CE-based companies are characterized by:

- using CAD/CAE tools for analysis of design concepts and their effective communication to others,
- employing people with specialties but who can work in team environments,
- allowing teams to have wide memberships but also a high degree of autonomy,
- encouraging their teams to follow structured and disciplined (but parallel) design processes,
- reviewing the progress of designs via milestones, deliverables and cost.

The conceptual design phase should receive input from individuals with diverse (but complementary) backgrounds; a typical example of product development team structure being presented in Fig.2.

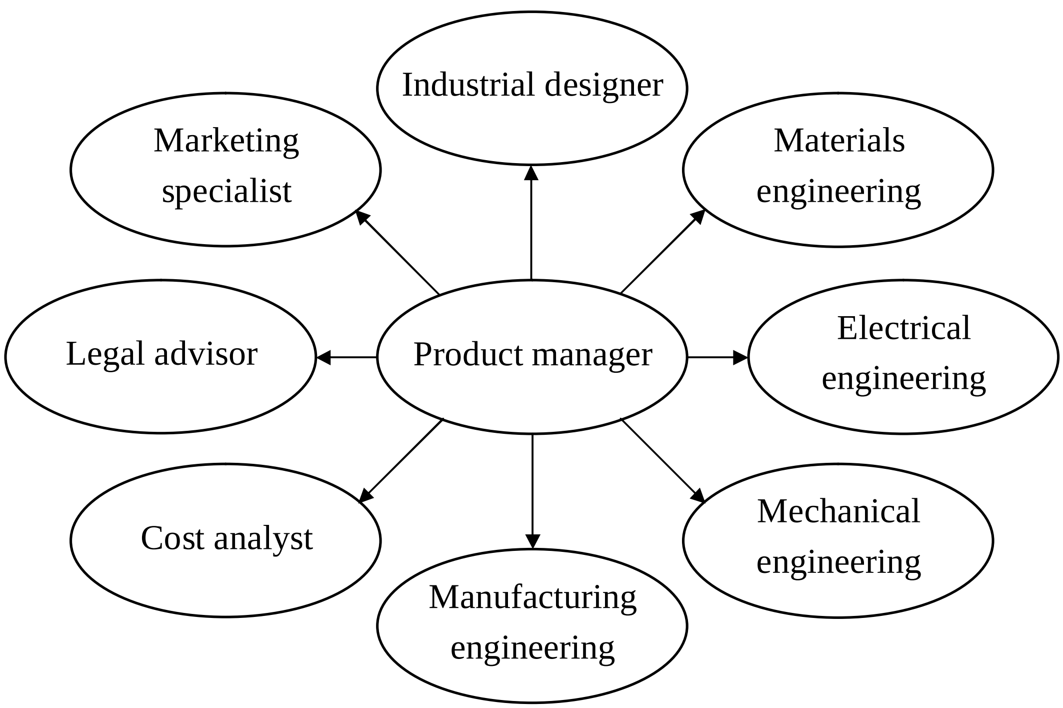


Fig.2: Product development team structure

Designs should allow continuous improvement based on potential future feedback. Product features should be designed in anticipation of imperfect use for *robustness*, and should be analyzed with respect to *manufacturability*, *assembly* and *human factors*. Product *modularity*, *standardization* and *interchangeability* should be considered as well.

Fabrication processes should be finalized concurrently with product design selection. Production plans and capacities should respect marketing efforts and aim for short lead times (for delivery).

II.1.2. Concept Development Process

Conceptual design includes many activities carried out by a variety of people with different knowledge areas, having the final objective of creating a profitable product. Fabrication designers and human-factor engineers are normally involved at this stage of (conceptual) design and preliminary prototyping in order to provide timely input to the product design team.

The first step in this process is customer-need identification and the second is concept generation and selection.

The process of customer-need identification must be carried without attempting to develop product specifications. The latter can only be decided upon once a concept is chosen and preliminarily tested to be technologically feasible and economically viable.

Gathering useful data from the customer may include interviews with a select (representative) group in order to identify all their requirements, preferably in a ranked order.

Naturally, need identification is an iterative process that involves returning to the base group with more questions following the analysis of earlier collected data.

Concept generation follows the step of customer-need identification and development of some functional (target) specifications based on the experience and know-how of the product design team members. They may search through existing similar products, technologies and tools for clues. At this stage, it is natural to develop (in an unrestricted way) as many concepts as possible and not dismiss any ideas using *brainstorming* method. Then can be concluded, however, with a methodical review of all data/ideas/proposals in order to narrow the field of options to a few conceptual design alternatives.

The final “winning” concept selection process is a critical stage in product design and does not necessarily imply the rejection of all in favor of one. This stage seeks a wider input from manufacturing engineers and (future) product-support group members in order to rank all proposals.

Preliminary prototyping (physical or virtual) may be necessary in order to consult with potential customers and evaluate usability (or even quality) of the selected product design concept.

II.1.3. Industrial Design

Industrial design can be defined as the professional service of creating and developing concepts and specifications that optimize the function, value and appearance of products and systems for the mutual benefit of both user and producer.

The following objectives have been commonly accepted by the industrial design community:

- *Appearance:* The form, styling and colors of the product must convey a pleasing feeling to the user.
- *Human factors:* The ergonomic and human-interface design of the product should facilitate its utilization in a safe manner.
- *Maintenance:* Design features should not hinder maintenance and repair.

Other important factors include minimization of manufacturing costs through the utilization of appropriate materials and easy-to-produce form features. Most companies would also prefer to convey a corporate identity that is easily recognizable by the customer, through the productôs design.

The intensity of industrial design in the development of a product is a direct function of its future utilization, namely, the characteristics of the customer.

As a vital member of the overall product design team, an industrial designerôs first task is the evaluation of customer needs during the concept development phase. Industrial designers are expected to have the necessary skills to interview customers and research the market for identifying the needs clearly, and communicate them to the engineers. At the concept generation phase, they concentrate on the form and human interfaces of the product, while engineers are mostly pre-occupied with addressing the functional requirements. Having an artistic background, industrial designers can also take a hands-on approach in generating alternative prototype models for conveying form and aesthetic requirements.

Once the field of design alternatives has been narrowed down, industrial designers return to their interactions with customers for collecting vital information on the customersô views and preferences regarding the individual concepts. At the final stages of the industrial design process, the role of the design engineers can vary from actually selecting the winning design and dictating the terms of manufacturing to simply participating in the marketing effort.

II.1.4. Human Factors in Design

Interactions between people and products can be classified into three categories: occupying common space, acting as a source of input power and acting as a supervisory controller. Human factors must be considered for every possible interaction, whether it being simply the operation of the product or its manufacture.

Designers must analyze their products for evaluation of hazards, preferably for their subsequent elimination and, when impossible, for their avoidance. The following hazards could be noted in most mechanical systems: kinematic (moving parts), electrical, energy (potential, kinematic and thermal), ergonomic/human factors (human-machine interface) and environmental (noise, chemicals, and radiation).

Safety of the person and quality of the product are the two paramount concerns. As noted above, if a hazard cannot be eliminated through design, the human users of the product should be provided with sufficient defense for hazard avoidance and with clear feedback, via signs, instruction or warning sensors to indicate the potential for a future hazard.

Of the three mentioned above, for interactions of the first type, designers must carefully analyze available statistical data on the human metrics (anthropometric data) in order to determine the optimal product dimensions and to decide where to introduce reconfigurability.

People often interact with their environment through touch: they have to apply force in opening a car door, twisting a bottle cap, or carrying boxes or parts on the shop floor. As with available human metrics for height, weight, reach, etc., there also exist empirical data on the capability of people in applying forces while they have different postures.

Safety is also a major concern here. Products and processes must be designed ergonomically in order to prevent unnecessary injuries to the human body, especially in the case of operators who carry out repetitive tasks.

Supervisory control of machines and systems is the most common human/machine interaction. In such environments, people monitor ongoing machine activities through their senses and exercise supervisory control (when necessary) based on their decisions. The issues of sensing and control, thus, should be first individually examined. (With significant advances in artificial sensing and computing technologies, today, many supervisory control activities are carried out by computer controlled mechanical systems when economically viable, or when people cannot perform these tasks effectively.

Representative issue that a designer must consider in designing human/machine interfaces refers to:

Clear and unambiguous display of sensory data: Displays should be clear, visible, and large. Analog displays are easier for quick analysis of a phenomenon, whereas digital displays provide precise information. Additionally, we must note that the number of colors easily distinguishable by the human eye is less than ten; the visual field extends 130º vertically and about 200º horizontally; it takes about half a second to change focus, a moving objectǒs velocity and acceleration greatly reduce its accurate positioning; the hearing range is between 20 and 20,000 Hz, and noise above 120 dB would cause discomfort if listened to by more than a few minutes.

Simplification and constraining of tasks: Control operations must involve a minimum number of actions. Where the possibility of incorrect actions exists, they should be prevented by clever design.

Suitable placement of input devices: Control devices, such as levers and buttons, should be placed for intuitive access and be easy to notice and to differentiate.

Providing feedback of control actions: The operator should be provided with a clear feedback (light or sound) in response to a control action undertaken, especially in anticipation of unwanted actions (where these cannot be physically prevented).

In order to cope with emergencies, we must also be aware of the information-processing limitations of human operators. As expected, people's information processing efficiency is significantly degraded when performing repetitive, boring tasks. General tiredness and personal stress further degrades this efficiency. The human operator is restricted in recalling from memory a task to be done within the next very short period of time. This phenomenon is further complicated if the necessary operation requires multiple subtasks. Thus, at emergencies, people react according to expected stereotypical actions. For example, they expect an increased reading with a clockwise dial display, push a switch upward for "on" and press down a brake pedal for stopping.

II.1.5 Conceptual Design Process

Design projects can be classified broadly as:

- varying a product by modifying one or more of its parameters, but maintaining its overall functionality and performance,

- redesigning a product by improving its performance, a large number of its characteristics, and/or its quality,

- development of a new product, whose development process (design and materials) is affected by the expected production level (batch versus large volume),

- made-to-order design of a product.

No matter which category the project falls into, however, the first step in the conceptual design process is *problem formulation*, followed by *concept generation* and *concept evaluation and selection* phases.

- *Problem Formulation*

Problem formulation must not be treated as an intuitive and trivial step of the engineering design process. One can never overemphasize this stage of identifying a customer's needs, which should be carried out with great care.

Since design must yield an optimal solution to the problem at hand, the objective and constraints of the problem must be defined.

Example: *development of a Walkman* – the overall goal could have been stated as "providing individuals with a device capable of replaying tape/CD-recorded music, while they are mobile, with a carry-on power source and in a private listening mode". From an engineering perspective, there would exist several objectives to satisfy this overall goal. The unit must have its own (preferably integral) power source, provide earphone connection and of course be affordable. Typical constraints for this example product would be size, weight and durability.

The technical literature provides us with numerous empirical and heuristic techniques for analyzing the problem at hand (as defined by the customer) and relate the customer requirements to engineering design parameters. Quality function development (QFD) is such a technique, first developed in Japan, that utilizes a chart representation of these relationships.

The primary elements of the QFD chart are:

- a list of the characteristics of the design as explained by the customer;
- a list that is generated by the engineers in response to the customer requirements;
- a comparison process to competitorsô similar products;
- a set of target values for engineering requirements.

Customer needs are normally expressed qualitatively or in fuzzy terms, whereas engineering characteristics are usually quantitative. Engineers are required to determine the functional requirements of the product that influence the needs expressed by the customer. These requirements can be qualitative (an acceptable form at the conceptual design phase) or expressed as ranges (with possible extreme limits). Functional requirements can express goals and constraints in the following categories: performance, (geometrical) form and aesthetics, environmental and life cycle, and manufacturability. Performance requirements would include goals on output (rate, accuracy, reliability, etc.), product life, maintenance and safety. Form requirements refer to physical space and weight and industrial-design issues. Manufacturability requirements refer to the determination of fabrication and assembly methods that need to be employed for a profitable product line.

- *Concept Generation*

The conceptualization stage of design can benefit from uninhibited creative thinking combined with wide knowledge of engineering principles and of the state of the art in the specific product market. Creativity is not a (scientifically) well understood process, though it has been researched by numerous psychologists.

The Creative Education Foundation model has five stages that form a sequential process:

- fact finding,
- problem formulation,
- idea finding (narrowing of ideas toward feasible solutions),
- evaluation,
- acceptance finding (pre-manufacturing stage of design).

- *Concept Evaluation and Selection*

Concept selection is one of the most critical decision-making exercises in a product development. One can appreciate the difficulty a design team faces in decision making, during the concept evaluation phase, without having the engineering design specifications to compare the alternative concepts. Quantifying designs based mostly on intangible criteria is the task at hand.

Pugh's method of concept selection, for example, evaluates each concept relative to a "reference concept" and rates it (according to some criteria) as being better (+), about the same (S), or poor (-), Table 1.

The evaluation process starts by choosing the criteria based on the engineering requirements or, if these are underdeveloped, based on the customer requirements. The criteria can be ranked without attempting to assign specific weights. The next step would be choosing a reference concept (preferably the "best" perceived concept).

Table 1: Pugh's method of concept selection

	Ref. concept	Concept 1	Concept 2	Concept 3	Concept 4
Criterion 1	S	+	-	S	-
Criterion 2	S	-	-	S	+
Criterion 3	S	S	+	+	S
Criterion 4	S	+	S	+	-
×(+)	0	2	1	2	1
×(-)	0	1	2	0	2
×(S)	4	1	1	2	1

The evaluation stage of the process, then, requires comparison of each concept to the reference according to the criteria chosen by the product team and the assignment of the corresponding score (+, S, or -). Based on the assigned scores, one ranks all the concepts and redefines the reference concept as the best among the ranked. The procedure would then be repeated with the new reference concept as our new comparison concept and stopped, eventually, if the repeated evaluations yield the same reference concept. At that time, the design team may simply decide to proceed with one or with the top concepts to the next product design stage.

Main characteristics of Pughôs method on concept selection are:

- Effective for comparing alternative conceptse
- scores concepts relative to one another
- iterative evaluation method
- most effective if each member of a design team performs it independently and results are compared.

II.1.6. Modular Product Design

When designing a system synthetically (such as an electronic machinery), the system could be designed by two broad ways. The first way would be to design the complete system using the known theories, and use the system, as it is designed, in the real conditions. An alternative way would be to design the different components of the system separately and test each component in separate conditions. *Modular design* or "*modularity in design*" is an approach that subdivides a system into smaller parts (modules or skids) that can be independently created and then used in different systems to drive multiple functionalities.

A modular system can be characterized by the following:

- functional partitioning into discrete scalable, reusable modules consisting of isolated, self-contained functional elements;
- rigorous use of well-defined modular interfaces, including object-oriented descriptions of module functionality;
- ease of change to achieve technology transparency and, to the extent possible, make use of industry standards for key interfaces.

Besides *reduction in cost* (due to lesser customization and less learning time), and *flexibility in design*, modularity offers other benefits such as *augmentation* (adding new solution by merely plugging in a new module), and *exclusion*.

Examples of modular systems are cars, computers, process systems, and high rise buildings. Earlier examples include looms, railroad signaling systems, telephone exchanges, pipe organs and electric power distribution systems. Computers use modularity to overcome changing customer demands and to make the manufacturing process more adaptive to change. A computer is actually one of the best examples of modular design; typical modules are power supply units, processors, mainboards, graphics cards, hard drives, optical drives, etc. All of these parts should be easily interchangeable as long as you use parts that support the same standard interface as the part you replaced.

Modular design is an attempt to combine the advantages of standardization (high volume normally equals low manufacturing costs) with those of customization. A downside to modularity (and this depends on the extent of modularity) is that modular systems are not optimized for performance. This is usually due to the cost of putting up interfaces between modules.

Standardization has long been a cost-saving measure, normally implemented at the component level for integral designs. Modular product design elevates standardization to the level of functional elements, where they can be used in different product models to carry out the same functions, allow easy replacement and provide expansion (add-on) capability.

One can conclude that product (design) modularity is a necessary step in achieving tactical flexibility in a manufacturing environment and providing customers with economically viable variety.

The Six Degrees of Modularity

There exist six degrees (levels) of modularity (Fig. 3):

- *Component Sharing Modularity*: This is the lowest level of standardization; the same components (e.g., motors and clutches) are used across many products (which may be modular or integral in design).

- *Component Swapping Modularity*: This is a component sharing modularity approach built around a single core product. Great numbers of variations can be presented to the customers (almost approaching a one-of-a-kind product line). The ñ*Swatch”* family of watches is a typical example.

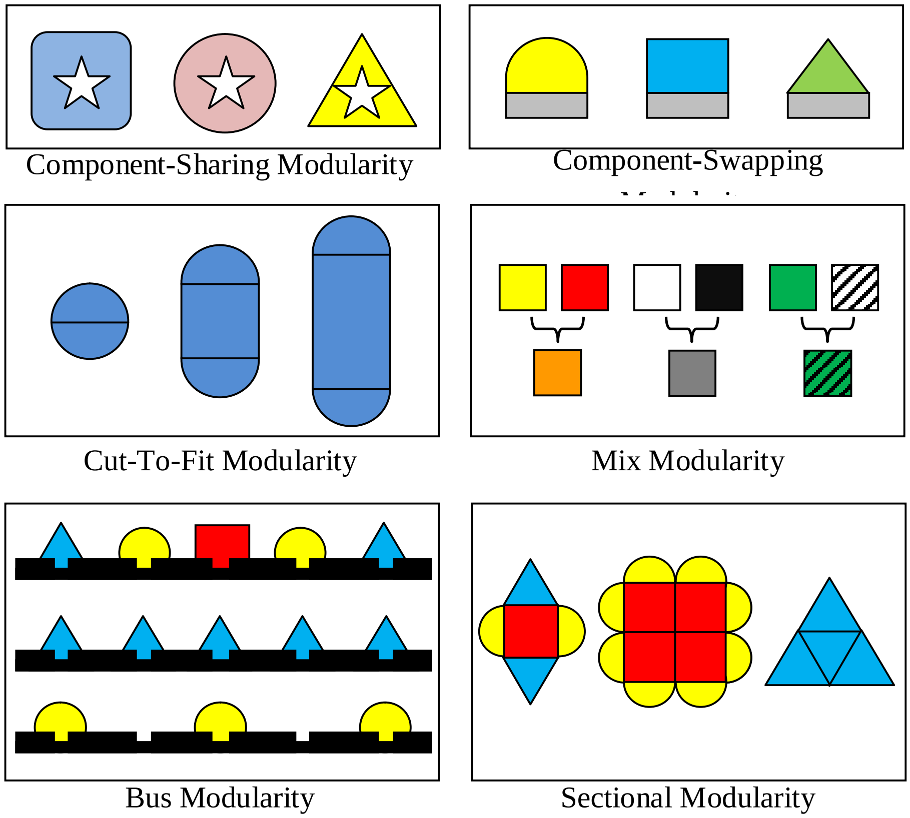


Fig.3: The Six Degrees of Modularity

- *Cut-To-Fit Modularity*: This is a parametric design variability achieved by customizing a small number of geometric features on the product.

- *Mix Modularity*: The product is simply a mixture of components, in which the components lose their identity within the final product. An exemplary application area could be the gathering of different electric components (diodes, thyristors, resistors, coils, capacitors, microprocessors, etc. in an electric device such as a frequency converter.

- *Bus Modularity*: Similar to mixing, a mixture of components is assembled on a óómotherôô bus/board/platform. Typical examples include computers and automotives. Naturally, modularity can only be achieved through a flexible design of the bus.

- *Sectional Modularity*: This is the ultimate level of modularity, where the productôs architecture is reconfigurable itself (as opposed to being fixed). Individual modules are configured to yield different products. The most common example is the reconfiguration of software modules to yield different application programs.

Modular Design Process

A three-step procedure has been commonly proposed for developing a modular product architecture:

- Create a schematic representation of the product, which normally would comprise a set of functional objectives as opposed to physical building blocks (or their components).

- Group the functional objectives into functional clusters, where possible. At this stage the designer can consider issues such as physical relationships (and proximity) between components, the potential for standardization, and even the capability of suppliers to provide clusters.

- Create a rough geometric layout of the product in order to evaluate operational feasibility through analysis of the interactions between the clusters, as well as the feasibility of production and assembly while maintaining a high degree of quality and economic viability.

II.1.7. Mass Customization

Mass production adopted in the earlier part of the 20th century was based on the principles of *interchangeable parts, specialized machines* and *division of labor*. The focus was on improving productivity through process innovation. The primary objective was to reduce cost and thus cause an increase in demand. Most large companies ignored niche markets and customer desires, leaving them to the small companies.

This manufacturing management paradigm started to loosen its grip on most consumer industries around the ő60s and ő70s in response to developing global competition pressures. A paradigm shift toward customization was full blown by the late ő80s in several industries, naturally, at different levels. The objective was set on *variety and customization through flexibility and quick responsiveness*.

The key features of todayĝs marketplace are:

- fragmented demand (the niches are the market),

- low cost and high quality (customers are demanding high-quality products, not in direct relation to the cost of the product),

- short product development cycles,

- short product cycles.

The result is less demand for a specific product but increased demand for the overall product family of the company, whose strategy is to develop, produce, market, and deliver affordable goods with enough variety and customization that almost everyone purchases their own desired product, like in mobile cell-phone and personal computers industries.

The primary (fundamental) prerequisite to achieving mass customization can be noted as having customizable products with modularized components.

In this context, standardization for customization is a competitive tool for companies marketing several related products, such as Black & Deckerؤs line of power tools, which use a common set of standardized subassemblies (clusters, modules, etc.).

The primary steps for the design of a mass customizable product are:

- *identifying customer needs*: This stage is similar to any product (concept) design stage with the exception of identifying potential personal differences in requirements for a common overall functional requirement for the product.

- *develop concepts*: Concepts (alternatives) should be developed and compared with a special emphasis for allowing modularity in final engineering design. (QFD and Pughؤs methods should be utilized.)

- *modularization of chosen concept*: The chosen design concept should be evaluated and iteratively modified with the objective of modularization (i.e., mass customization) and fit within the larger family of products, with which the proposed design will share modules.

II.2. Design Methodologies

Four primary design methodologies, developed in the past several decades for increased design productivity and the resultant product quality, are presented next.

Even if these methodologies are suitable and have been commonly targeted for the post-conceptual-design phase, some can also be of significant benefit during the conceptual design phase of a product. Axiomatic design methodology, for example, falls into this category.

Designers should attempt to use as many established design methodologies as possible during product development; for example: axiomatic design and group technology at the conceptual design phase, design for manufacturing/assembly/environment guidelines during configuration and detailed design and the Taguchi Method during parametric design.

II.2.1. Axiomatic Design Methodology

All design methods aim to lead a designer to one or more good solutions to a design problem. The design methodôs developer expresses his or her own beliefs about the best tactics for identifying good designs in the methodôs principles or major strategies.

Axiomatic Design was developed by Nam P. Suh, a mechanical engineering professor at MIT. Suhôs intention was to identify a set of fundamental laws or principles for engineering design and use them as the basis for a rigorous theory of design.

A design theory would make it possible to answer such questions as:

- Is this a good design?
- Why is this design better than others?
- How many features of the design must satisfy the needs expressed by the customers?
- When is a candidate design complete?
- What can be done to improve a particular design?
- When is it appropriate to abandon a design idea or modify the concept?

Axiomatic Design Introduction

Axiomatic Design operates with a model of the design process that uses state spaces to describe different steps in generating design concepts.

Consumer Attributes (CAs) ï Variables that characterize the design in the consumer domain. CAs are the customer needs and wants that the completed design must fulfill. These are similar to the customer requirements.

Functional Requirements (FRs) ï Variables that characterize the design in the functional space. These are the variables that describe the intended behavior of the device. However, there is no standard set of FRs from which a designer must choose.

Design Parameters (DPs) ï Variables that describe the design in the physical solution space. DPs are the physical characteristics of a particular design that has been specified through the design process.

Process Variables (PVs) ï Variables that characterize the design in the process (fabrication) domain. PVs are the variables of the processes that will result in the physical design described by the set of DPs.

Fig.4 indicates the relationships between these different variables throughout the Axiomatic Design process.

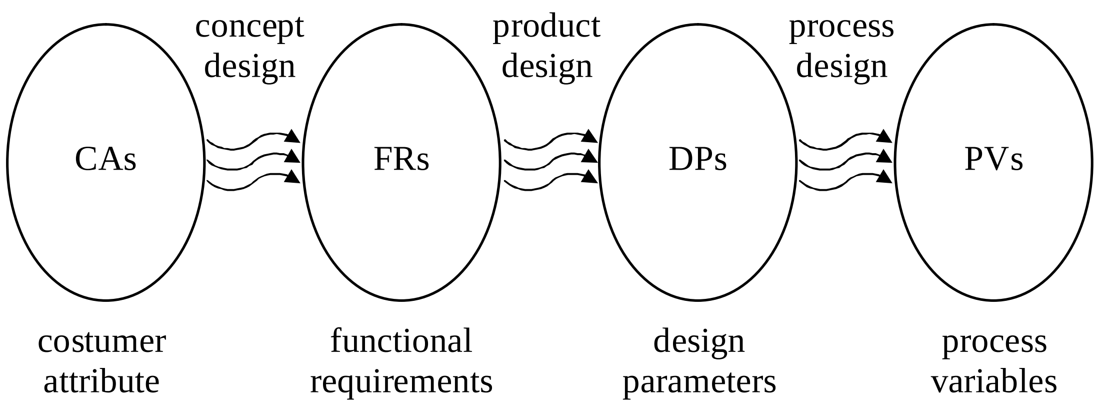


Fig.4: The design process from an Axiomatic Design perspective

Suh views the engineering design process as a constant interplay between what we want to achieve and how we want to achieve it. The former objectives are always stated in the functional domain, while the latter (the physical solution) is always generated in the physical domain.

The Axioms

In mathematics, an axiom is a proposition that is assumed to be true without proof for the sake of studying the consequences that follow from it. Theorists working in mathematically based fields declare a set of axioms to describe the ideal conditions that are presumed to exist and must exist to support their theories. Many economic theories rest on presumptions that corporations act with perfect knowledge of their markets and without exchanging information with their competitors.

More generally, an axiom is an accurate observation of the world but is not provable. An axiom must be a general truth for which no exceptions or counterexamples can be found. Axioms stand accepted, based on the weight of evidence, until otherwise shown to be faulty.

Suh has proposed two conceptually simple design axioms in Axiomatic Design:

- *Axiom 1* named *the independence axiom:* It can be stated in a number of ways:

- An optimal design always maintains the independence of the functional requirements of the design.

- In an acceptable design the design parameters (DPs) and functional requirements (FRs) are related in such a way that a specific DP can be adjusted to satisfy its corresponding FR without affecting other functional requirements.

- *Axiom 2* is *the Information axiom:* The best design is a functionally uncoupled design that has the minimum information content.

Axiom 2 is considered as a second rule for selecting designs. If there is more than one design alternative that meets Axiom 1 and has equivalent performance, then the design with the lesser amount of information should be selected.

Many users of Axiomatic Design focus on value and the implementation of the independence axiom. The function focus of Axiom 1 is more fundamental to engineering designers and the relationships between functional requirements and physical design parameters are also clear. Axiom 2 has been adopted more slowly and is still the subject of interpretation.

As a way to categorize designs, Suh also introduced the following design categories that will be later explained:

- *Uncoupled design:* A concept that satisfies Axiom 1.
- *Coupled design*: A concept that violates Axiom 1, where a perturbation in a DP affects multiple FRs.
- *Decoupled design*: A concept that is initially a coupled design due to lack of sufficient DPs, but one that can be decoupled with the use of extra DPs.

Using Axiomatic Design to Generate a Concept

The Axiomatic Design procedure is a mapping of one set of variables to another. A type of design specification is obtained by examining the customerꞌs needs and expressing them as a list of attributes. These attributes are mapped into a set of functional requirements. This process is labeled concept design in

Suh's design process schematic shown in Fig.4. In this text we have considered the mapping of customer needs into functional requirements to be a prerequisite step that takes place prior to the generation of feasible concepts.

The design parameters (DPs) depict a physical embodiment of a feasible design that will fulfill the FRs. As Fig.4 illustrates, the design process consists of mapping the FRs of the functional domain to the DPs of the physical domain to create a product, process, system or organization that satisfies the perceived societal need.

Note that this mapping process is not unique. Therefore, more than one design may result from the generation of the DPs that satisfy the FRs. Thus, the outcome still depends on the designer's creativity. However, the design axioms provide the principles that the mapping techniques must satisfy to produce a good design, and they offer a basis for comparing and selecting designs.

Using Axiomatic Design to Improve an Existing Concept

Previously, it was presented the way Axiomatic Design provides a framework for generating one design concept from a set of functional requirements. The designer is supposed to be aware of the axioms during this process, but the axioms may be overlooked. But, how Axiomatic Design's formulation of the design process mapping steps, using matrix algebra allows designers to develop insight about their design concepts and determine how to improve them? Nam Suh used mathematics to formalize his work in Axiomatic Design. The following equation articulates any solution to a given design problem.

$$\{FR\} = [A]\{DP\} \qquad [1]$$

In Eq.1, the vector of function requirements (FR), consists of *m* rows and 1 column, and the vector of the design parameters (DP), is of size *n* rows and 1 column. The design matrix (A), is of size *m* rows and *n* columns and holds the relationships between members of the two vectors as defined in the next equation.

$$[A] = \begin{bmatrix} A_{11} & A_{12} & A_{13} & A_{14} & \dots & A_{1n} \\ A_{21} & A_{22} & A_{23} & A_{24} & \dots & A_{2n} \\ A_{31} & A_{32} & A_{33} & A_{34} & \dots & A_{3n} \\ A_{41} & A_{42} & A_{43} & A_{44} & \dots & A_{4n} \\ \dots & \dots & \dots & \dots & \dots & \dots \\ A_{m1} & A_{m2} & A_{m3} & A_{m4} & \dots & A_{mn} \end{bmatrix}, \text{ where: } A_{ij} = \frac{\partial FR_i}{\partial DP_j} \qquad [2]$$

Each element in the design matrix (A_{ij}) represents the change in the i^{th} functional requirement due to the value of the j^{th} design parameter. Note: this is the theoretical formulation of a design matrix under ideal conditions. There is no expectation that a specific value exists for any (A_{ij}) term. The formulation is powerful because of the insight it brings to the design problem even when it is analyzed with symbols and not numerical values. Axiomatic Design does not require that the equation can be solved for values of any of the terms.

The equation format for a design solution given in Eq.1 allows users to define the relationship of any FR to the set of DPs. This is shown in Eq.3.

$$FR_i = \sum_{j=1}^{n} A_{ij} DP_j = A_{i1} DP_1 + A_{i2} DP_2 + \cdots + A_{in} DP_n \qquad [3]$$

Like some other design methods, Axiomatic Design decomposes the design problem. From Eq.3 it is clear that the design team must set the values of all relevant design parameters (DPs) at levels that will achieve the desired value of the functional requirement FR_i. The fact that some of the A_{ij} values are zero gives a design team insight into their design problem. For example, if only one term is nonzero in Eq.3, then only one design parameter must be set to satisfy FR_i.

Axiomatic Designôs representation of a solution concept provides another way to describe the design axioms. The independence axiom states that acceptable designs maintain independence among the functional requirements. That means, to uphold the functional requirementsô independence, each design parameter (DP) can be set to satisfy its corresponding FR without affecting other functional requirements. That means no design parameter should contribute to satisfying more than one functional requirement.

Any concept that satisfies Axiom 1 will have a diagonal design matrix like the one in Eq.4.a. This also implies that an ñidealò design for satisfying Axiom 1 is one that provides one and only one DP for the satisfaction of each FR. This type of design is *uncoupled*, but it is rare to find in engineering where the behavior of each component is leveraged to serve as many aspects of required functionality as possible. In some designs, the components are so integrated that every DP materially contributes to each FR. Such a design is coupled, and its matrix would be like the one in Eq.4.c. Most designs fall into a middle category of being not *fully coupled* (i.e., some elements of [A] are equal to zero), but the design matrix is not diagonal.

Some of the coupled designs belong in a third category, *decoupled* designs. There are designs with some dependence among their functional requirements, but the dependencies are such that there is an order of decision making for the design parameters that minimized the dependence. A decoupled design is one that has a triangular design matrix as shown in Eq.4.b. The equations beside the triangular matrix highlight that that the DPs can be set in the order of DP_3, DP_2, then DP_1 to achieve a lesser degree of dependence among the FRs. Decoupled designs require reconsideration of all DP values when any one must change. Yet it is easier to create a decoupled design than an uncoupled design.

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{Bmatrix} = \begin{bmatrix} A_{11} & 0 & 0 \\ 0 & A_{22} & 0 \\ 0 & 0 & A_{33} \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{Bmatrix} \quad [4.a]$$

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{Bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ 0 & A_{22} & A_{23} \\ 0 & 0 & A_{33} \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{Bmatrix} \quad [4.b]$$

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{Bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{Bmatrix} \quad [4.c]$$

Suh also developed corollaries from the axioms that suggest ways to improve the independence of functional requirements. Here are a few corollaries with short descriptions:

- *Corollary 1:* Decouple or separate parts or aspects of a solution if FRs are coupled in the proposed design. Decoupling does not imply that a part has to be broken into two or more separate physical parts, or that a new element has to be added to the existing design.
- *Corollary 2*: Integrate design features in a single physical part if FRs can be independently satisfied in the proposed solution.
- *Corollary 3*: Use standardized or interchangeable parts if the use of these parts is consistent with the FRs and constraints.
- *Corollary 4*: Use symmetric shapes and/or arrangements if they are consistent with the FRs and constraints. Symmetrical parts require less information to manufacture and to orient in assembly.

Strengths and Weaknesses of Axiomatic Design

Axiomatic Design is useful in focusing the designer or design team on the core functionality required in a new product. The method provides tools for classifying existing designs once they are represented in the key design equation that uses the design matrix to relate functional requirements to design parameters. Axiomatic Design is also one of the most widely recognized design methodologies, especially within the academic community (where it originated).

As with the other design methods, there are strengths and weaknesses in Axiomatic Design. The strengths are rooted in the mathematical representation chosen by Suh:

- Mathematically based ï Axiomatic Design is built with a mathematical model of axioms, theories and corollaries. This meets the need of the design theory and methodology community to incorporate rigor in the field.
- Vehicle to relate FRs and DPs ï The representation of designs using FRs, DPs, and the design matrix [A] opens up their interpretation in mathematical ways more common to students of linear algebra.
- Powerful if the relationship is linear ï the design matrix [A] is a powerful conceptual tool and is also a reminder that there may be some relationships of FRs and DPs that are understood to the point of mathematical expression. If others arenôt, itôs still a goal.
- Provides a procedure for decomposing decision process ï Reviewing the design matrix [A] can reveal natural partitions in the setting of FRs that will aid in ordering the efforts of the design team.
- Basis for comparing alternative designs ï Axiomatic Design provides a metric (degree of independence of functional requirements) that can be used to differentiate between competing designs concepts.

Weaknesses of Axiomatic Design lie first in the fact that the axioms must be true in order to accept the methodology. There is no proof that the independence axiom is false, but there are examples of designs that are strongly coupled and are still good designs in the eyes of the user community. Other weaknesses are as follows:

- The design method describes a way to create new designs from FR trees to DPs. Yet the methodology is not as prescribed as others (e.g., systematic design). This can lead to a problem with repeatability.

- Designs are usually coupled ï This echoes some concern for the strength of Axiom 1 and also means that it will be difficult to decouple existing designs to create improvements.
- Axiom 2: Minimize Information Content is difficult to understand and apply. There are many approaches to interpreting Axiom 2. Some designers use it to mean complexity of parts, others use it to mean reliability of parts, still others have considered it to refer to the ability to maintain the tolerances on parts. Axiom 2 has not been used by the design community as much as Axiom 1, leading to questions about its usefulness or about the axiomatic approach in general.

Regardless of the open questions of Axiomatic Design, the overall message holds true: The best design of all equivalent designs is a functionally uncoupled design having the minimum information content.

The above should be seen as guidelines to be used in conjunction with numerous design rules to be specified in this chapter to satisfy objectives, such as manufacturability, ease of assembly and environment friendliness.

II.2.2. Specific Process Design Methodology

Presently, it is commonly accepted that consideration of manufacturing and assembly issues during the design phase of a product is a fundamental part of concurrent engineering (CE).

The main objective here is to briefly introduce specific process design methodologies, which must follow some general design guidelines:

- Design parts for fabrication process simplification ï select materials and corresponding fabrication processes suitably.

- Specify tolerances, surface finish and other dimensional constraints that are realistic.

- Minimize the number of parts, and furthermore use as many as standard parts as possible.

- Mechanical properties are affected by specific production process.

- ***Design for Manufacturing***

Consideration of manufacturing (also termed as production or fabrication) processes during the design stage of a product is fundamental to successful design. Since selection of materials must precede consideration and analysis of manufacturability, herein it will be assumed that this stage is part of the definition of functional requirements (in response to customer needs) and thus will not be addressed. Primary issues that arise during material selection include product life, environmental conditions, product features and appearance factors.

In order to illustrate the importance of considering manufacturability during the product development stage, a set of manufacturing processes will next be reviewed, specifically from the perspective of design guidelines.

Design for Casting

In casting, a molten metal is poured (or injected at high pressure) into a mold with a single or multiple cavities. The liquid metal solidifies within the cavity and is normally subject to shrinkage problems. A good mold design will thus have features to compensate appropriately for shrinkage and avoid potential defects.

Castings must be designed so that parts (and patterns for sand casting) can be removed easily from the cavities. Different sections of a part with varying thicknesses should have gradual transitions. Projecting details should be avoided. Ribs should not be allowed to cross each other but should be offset. In die casting, parts should have thin-walled structures to ensure smooth metal flow and minimum distortion due to shrinkage. It should also be note that die casting is normally limited to nonferrous metals.

Furthermore, different casting techniques yield different dimensional accuracy and surface finish. For example, although sand casting can be used for any type of metal, poor surface finish and low dimensional accuracy are two of its disadvantages.

Design for Forging

Forging is the most common (discrete-part) metal forming process in which normally a heated part is formed in a die cavity under great (impact) pressure. Owing to the high forces involved, generally an assembly part is formed in multiple iterations. As with casting, vertical surfaces of a part must be tapered for ease of removal (normally done manually). Furthermore, rapid changes in section thicknesses should be avoided to prevent potential cracks. Finally, when designing a product that is to be forged, the location of the óóparting line,ôô where the two die halves meet, should be carefully chosen to influence positively the grain flow and thus the mechanical properties of the part.

Design for Machining

There is a variety of material-removal processes that are collectively called machining. Although both metals and plastics can be machined using turning, milling and grinding operations, machining is primarily reserved for metal parts. Cylindrical (rotational) geometries can be obtained using a lathe or a boring machine (for internal turning), whereas prismatic geometries can be obtained on a milling machine.

Machining is a flexible manufacturing operation in which metal-cutting parameters can be carefully controlled to produce almost any external detail on a (one-of-a-kind) part, including 3-D complex surfaces.

Automated machine tools can be programmed to fabricate parts in large quantities as well, such as nuts, bolts, and gears. Being material-removal techniques, such processes can take long periods of time when high accuracies are required and/or material hardness is very high. Thus a designer must carefully consider configuring features on a product that would require several setup activities, to rotate and realign the part, and subsequently long manufacturing times.

A common error in designing parts for machining is placement of holes (or other details) on a part that would not be accessible due to collision between the tool-holder and the part. It also should be avoided features or tolerances that a machine tools cannot profitably fabricate, internal features in long pieces (including cylindrical bores), and dimensional ratios that are very high.

Design for Injection Molding

Injection molding is the most common plastic-parts manufacturing process for thin-walled objects. It commonly utilizes (recyclable) thermoplastic polymer granules that are melted and forced into a mold cavity.

It is a very efficient process in which multicavity molds can manufacture several thousands of parts per hour and last for several millions of parts.

The three-step fabrication process comprises injection of molten plastic into the cavities, cooling (solidification) through the cavity walls, and forced ejection.

As in casting and forging, the two most important design considerations in injection molding are wall thicknesses and parting lines. Other design guidelines include configuring parts geometry for adequate tapers for easy ejection from the cavities; ensuring proper proportioning of wall thicknesses for minimum distortion during cooling; minimizing wall thicknesses (through the use of supporting elements) for fast cooling; avoiding depressions on the inner side surfaces of the part to simplify mold design and minimize cost.

- ***Design for Assembly***

Assembly is a fabrication process normally seen as an activity that does not add value to the final product. Thus every effort should be made to minimize assembly costs by reducing the total number of parts and avoiding multiple directions of assembly.

Regarding design for assembly, the guidelines specified above addresses the issues of parts manipulation and joining:

- Design parts with geometrical symmetry, and if not possible exaggerate the asymmetry.
- Avoid part features that will cause jamming and entanglement, and if needed add nonfunctional features to achieve this objective.
- Incorporate guidance features to partȏs geometry for ease of joining.
- Design products for unidirectional vertical (layered) assembly in order to avoid securing the previous subassembly while turning it.
- Incorporate joining elements into the parts (such as snap fits) in order to avoid holding them in place when utilizing additional joining elements (such as screws, bolts, nuts, or even rivets).
- Snap fits can be designed to allow future disassembly or be configured for permanent joining owing to potential safety reasons.

The major cost of assembly is determined by the number of parts in the product. Thus one should first and foremost attempt to eliminate as many parts as possible, primarily by combining them. The possibility of elimination can be recognized by examining the product (Does the part move after the assembly, or simply remain static? Why must the part be of a different material than the neighboring part? Would the part prevent the assembly of other parts, by presenting an obstruction, if it were to be combined with a neighboring part?).

As argued by the axiomatic design theory, eliminating parts from a product is in line with Axiom 2, which requires minimization of information. Integration of parts (consolidation) may also reduce typical stress concentration points in parts owing to the use of external fasteners.

Another advantage of part reduction is the elimination of future potential loosening in joints and subsequent vibration noise.

- ***Design for the Environment***

Human population growth is a major factor in the well-being of our environment, and when coupled with the complexity of our lifestyles it presents an enormous pressure on the worldös precious resources.

In the past century, the worldös industrial production grew more than 100 times. In the same period of time, the consumption of fossil fuel increased by a factor of more than 50 times. It has been eagerly argued that we cannot continue to use materials and resources at their current rates without experiencing severe shortages within the next 50 to 100 years.

Any industrial activity has an environmental impact: from the materials it uses, to the products it manufactures, which have to be dealt with at the end of their life cycles as wastes. The manufacturing process itself generates over 10% of the total global wastes (Fig.5).

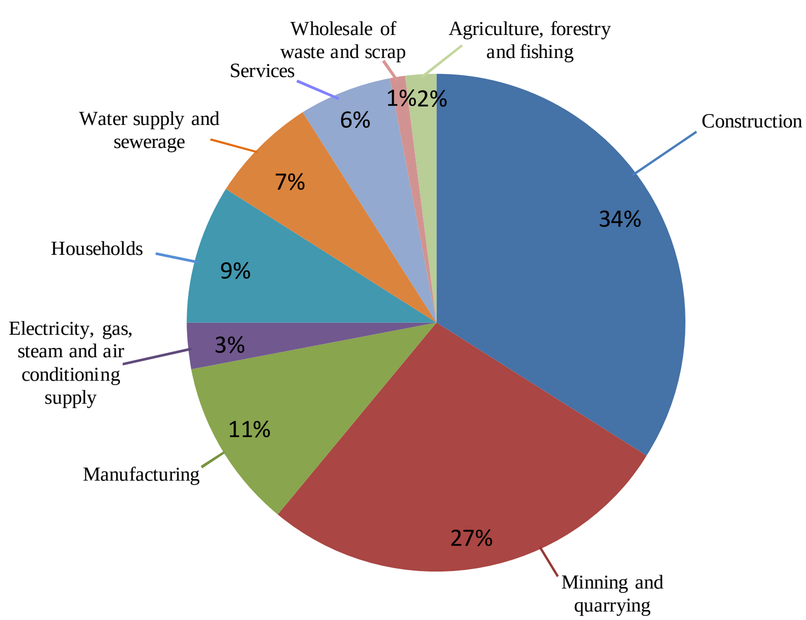


Fig.5: Waste generation by economic activity and households

The approach to industrial-environmental interactions is commonly referred to as *industrial ecology*. It aims at designing industrial processes and products that minimize their impact on the environment, while maintaining manufacturing competitiveness. In that respect, one must be concerned about the following global issues: climate change, ozone depletion, loss of habitat and reductions in biodiversity, soil degradation, precipitation acidity, and degradation of water and air qualities.

A primary issue in industrial ecology is life cycle assessment (LCA), a formal approach to addressing the impact of a product on the environment as it is manufactured, used and finally disposed of. The first step of LCA is the inventory analysis, that needs to determine the inputs (materials and energy) used in manufacturing and the outputs (the product itself, waste and other pollutants) resulting during manufacturing and beyond. The second step of LCA is quantifying the impact of the outputs on the environment (a most contentious issue). The final step is the improvement analysis. Proposals are presented to manufacturers for reducing environmental impact.

The manufacturing industry uses a considerable amount of energy (around 24% of the total energy use) ï see Fig.6.

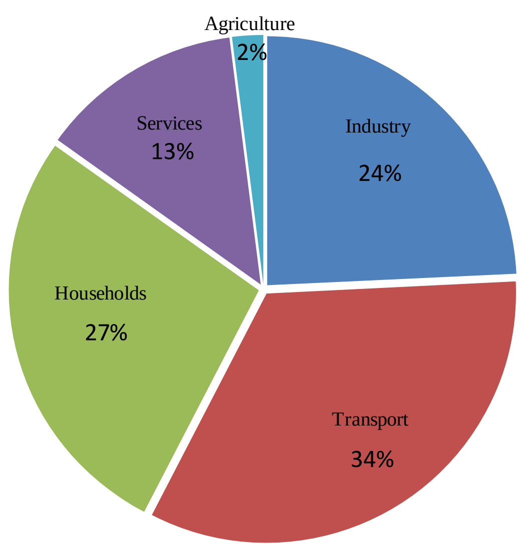


Fig.6: Energy consumption by sectors

The answer to energy-source selection is not a simple one, because uses of different resources (Fig.7) impact the environment at varied levels. As far as the atmosphere is concerned, for example, fossil-fuel combustion is more harmful than energy produced by nuclear power. That is, energy-source efficiency must often be balanced with toxicity concerns. However, no matter what its source of energy is, a manufacturing company must always aim for energy conservation when evaluating product design and fabrication process alternatives.

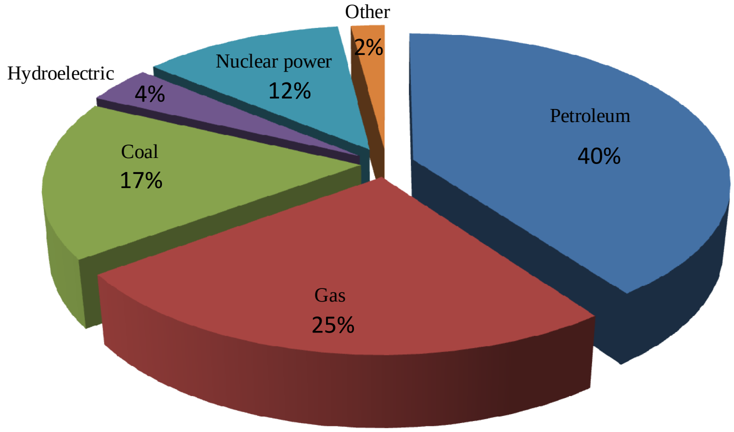


Fig.7: European Union Energy Production Sources

But, where all that energy goes? Over 50% of total energy consumption in the manufacturing industries is used by electric motors in different processing equipments (Fig.8). Another considerably percentage goes to building energy use (lighting, heating, ventilation and air conditioning - HVAC).

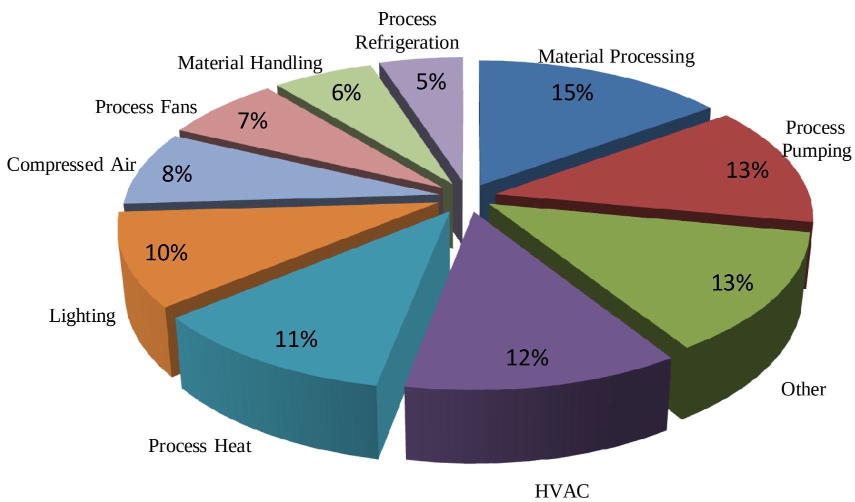


Fig.8: Manufacturing Energy End-Use Distribution

Presently, during many manufacturing processes, numerous toxic chemicals are released to the environment. These residues can be solid, liquid, and/or gaseous.

Solid residues come in several forms: product residues generated during processing (for example, small pieces of plastic or metal trimmings), process residues (such as cutting tools disposed of at the end of their useful life), and packaging residues (packaging and transportation material brought to the factory (drums, pallets, cardboard, etc.). Manufacturing companies should make every effort to minimize all waste (recycle waste material as well as utilize reusable packaging).

Although it is a difficult issue to tackle, designers can make an effort in choosing product materials for minimal environmental impact, especially in relation to their extraction as well as processing. Naturally, an efficient recycling operation may provide manufacturers with adequate material supply with lower costs and minimal environmental impact. Thus recyclability of the productọs material should be a factor in this selection. Today metals are recycled with reasonable efficiency, returning them to their original condition through rework (remanufacture) or at worst by melting them. No matter what materials are utilized, one should always strive toward minimization of their amount through suitable engineering design.

It is also important to reduce the number of different materials used in the manufacturing of a product and, where possible, to keep them separated for ease of joining and subsequent recycling.

Another important issue is *design for disassembly*. Two methods are used for common disassembly: *reversible* (where screws are removed, snap-fits are unsnapped, etc.) and *destructive* (where the joints are broken).

Economic and safety issues play major roles in deciding which joining technique to use. A modular design will greatly simplify the task of disassembly, because it will allow a quicker identification of the part/ component/subassembly to be replaced.

The design guidelines for *green* products and processes can be summarized as:

- *Increase efficiency of energy use, while considering environmental impact.*

- *Minimize the amount of materials used.*
- *Use recyclable and biodegradable materials where possible.*
- *Maximize the life expectancy of the product.*
- *Design a modular product for ease of disassembly and remanufacturing.*

II.2.3. Design of Experiments and Taguchi's Method

Parameter and tolerance design follows the conceptual design and engineering requirements. At this stage, most engineers review functional requirements and decide on parameter and tolerance values based on experience, handbooks, etc. In the case of multi-parameter design, however, where the choice of one parameter affects the other, engineers are advised to run experiments and optimize their values.

Experimentation (for optimization) can be accomplished in the *physical domain* or in *virtual space*, where numerical simulations are performed.

- ***Parameter Design Using Design of Experiments and Response-Surface Optimization***

It is strongly recommended that engineers take advantage of well-established statistical design of experiments (DOE) theories in order to minimize the search efforts for the optimal parameter values. The alternative would be to run a random (not well thought) set of experiments, from which one cannot easily deduct meaningful conclusions.

Most common classic DOE designs are considered to be: full factorial, response surface and mixture designs.

A *full factorial design* contains all possible combinations of a set of factors. This is the most fool proof design approach, but it is also the most costly in experimental resources. The full factorial designer supports both continuous factors and categorical factors with up to nine levels.

In full factorial designs, you perform an experimental run at every combination of the factor levels. The sample size is the product of the numbers of levels of the factors. For example, a factorial experiment with a two-level factor, a three-level factor, and a four-level factor has 2 x 3 x 4 = 24 runs.

Factorial designs with only two-level factors have a sample size that is a power of two (specifically 2^f where f is the number of factors). When there are three factors, the factorial design points are at the vertices of a cube as shown in the diagram below. For more factors, the design points are the vertices of a hypercube.

Full factorial designs are the most conservative of all design types. There is little scope for ambiguity when you are willing to try all combinations of the factor settings.

Unfortunately, the sample size grows exponentially in the number of factors, so full factorial designs are too expensive to run for most practical purposes.

Response surface designs are useful for modeling a curved quadratic surface to continuous factors. A response surface model can pinpoint a minimum or maximum response, if one exists inside the factor region. Three distinct values for each factor are necessary to fit a quadratic function, so the standard two-level designs cannot fit curved surfaces.

The most popular response surface design is the central composite design, illustrated in Fig.9.

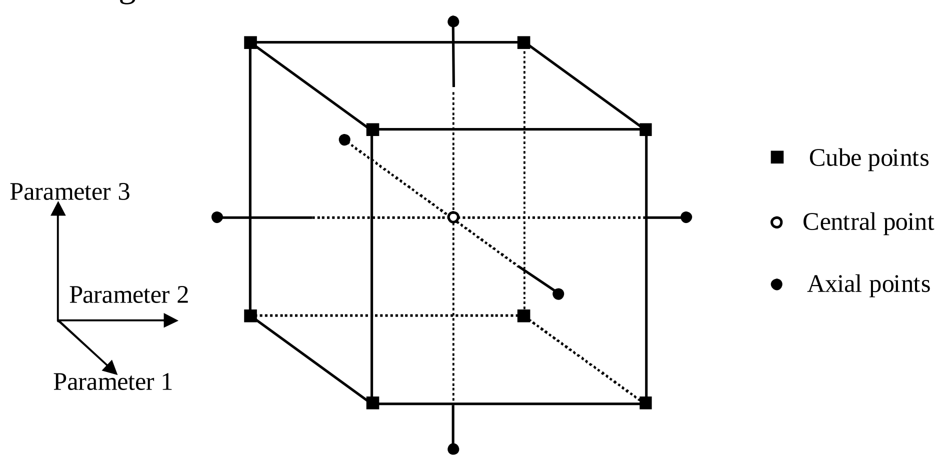


Fig.9: Central Composite Design

It combines a two-level fractional factorial and two other kinds of points:

- Center points, for which all the factor values are at the zero (or midrange) value.
- Axial (or star) points, for which all but one factor are set at zero (midrange) and that one factor is set at outer (axial) values.

The Box-Behnken design, illustrated in the Fig.10, is an alternative to central composite designs. One distinguishing feature of the Box-Behnken design is that there are only three levels per factor.

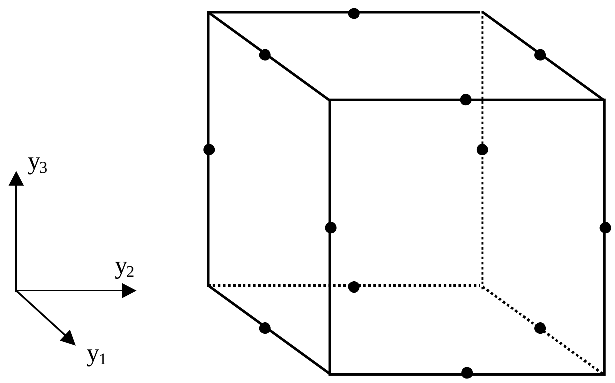


Fig.10: Box-Behnken design

Another important difference between the two design types is that the Box-Behnken design has no points at the vertices of the cube defined by the ranges of the factors. This is sometimes useful when it is desirable to avoid these points due to engineering considerations. The price of this characteristic is the higher uncertainty of prediction near the vertices compared to the central composite design.

The *mixture designer* supports experiments with factors that are ingredients in a mixture. You can choose among several classical mixture design approaches, such as simplex, extreme vertices, and lattice. For the extreme vertices approach you can supply a set of linear inequality constraints limiting the geometry of the mixture factor space.

The properties of a mixture are almost always a function of the relative proportions of the ingredients rather than their absolute amounts. In experiments with mixtures, a factor's value is its proportion in the mixture, which falls between zero and one. The sum of the proportions in any mixture recipe is one (100%).

With mixtures, it is impossible to vary one factor independently of all the others. When you change the proportion of one ingredient, the proportion of one or more other ingredients must also change to compensate. This simple fact has a profound effect on every aspect of experimentation with mixtures: the factor space, the design properties, and the interpretation of the results.

Because the proportions sum to one, mixture designs have an interesting geometry. The feasible region for the response in a mixture design takes the form of a simplex.

- ***The Taguchi Method***

Quality was the watchword of ó80s, and Genichi Taguchi was a leader in the growth of quality consciousness. One of Taguchiös technical contributions to the field of quality control was a new approach to industrial experimentation. The purpose of the Taguchi method was to develop products that worked well in spite of natural variation in materials, operators, suppliers and environmental change. This is called robust engineering.

Much of the Taguchi method is traditional. His orthogonal arrays are two-level, three-level, and mixed-level fractional factorial designs. The unique aspects of his approach are the use of signal and noise factors, inner and outer arrays, and signal-to-noise ratios.

The goal of the Taguchi method is to find control factor settings that generate acceptable responses despite natural environmental and process variability. In each experiment, Taguchiös design approach employs two designs called the inner and outer array. The Taguchi experiment is the cross product of these two arrays. The control factors, used to tweak the process, form the inner array. The noise factors, associated with process or environmental variability, form the outer array. Taguchiös signal-to-noise ratios are functions of the observed responses over an outer array. The Taguchi designer supports all these features of the Taguchi method. You choose from inner and outer array designs, which use the traditional Taguchi orthogonal arrays.

Dividing system variables according to their signal and noise factors is a key ingredient in robust engineering. Signal factors are system control inputs. Noise factors are variables that are typically difficult or expensive to control.

The inner array is a design in the signal factors and the outer array is a design in the noise factors. A signal-to-noise ratio is a statistic calculated over an entire outer array. Its formula depends on whether the experimental goal is to maximize, minimize or match a target value of the quality characteristic of interest.

Pictorially, we can view this design as being a conventional design in the inner array factors (Fig.11) with the addition of a "small" outer array factorial design at each corner of the "inner array" box.

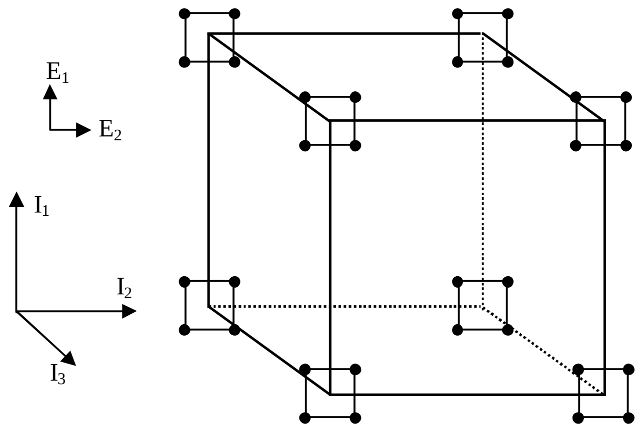


Fig.11: Taguchi Method

A Taguchi experiment repeats the outer array design for each run of the inner array. The response variable in the data analysis is not the raw response or quality characteristic; it is the signal-to-noise ratio.

Taguchi defines quality as an inverse function of a desired characteristic of a product and treats it as a loss. That is, every product has an associated quality loss, which could be zero if the product has the exact (expected) characteristics from the consumer's point of view. This quality "loss function" (for the output) is defined by *L(y)*. If one assumes that process noise is normally distributed and that the mean value of this distribution is the expected output value by the customer – nominal is the best – the loss function can be defined as:

$$L(y) = k(y - \mu)^2 \qquad [5]$$

where *k* is a cost coefficient defined by:

$$k = \frac{[illegible]}{[illegible]} \qquad [6]$$

The above concept of loss experienced by a customer, who expects the product to yield an output equal in magnitude to the mean, but which is actually a distance away from the mean ($y - \mu$). The product's output value, y, although it could be within its functional tolerance limits, defined by $y \pm \varphi_0$, still represents a loss to the customer, since it is not exactly equal to the mean value, where L(y) = 0.

Naturally, the coefficient k in [5] differs from product to product and would include cost elements such as replacement, repair, service, customer loyalty, etc. Thus it is difficult to measure.

The overall conclusion of Taguchiõs studies has been that: manufacturers must minimize the variability of their process as much as is economically viable, since customers do experience a loss in quality when they do not receive the mean output value that they expect. The tighter the process variability is, the higher the percentage of products within the (engineering) tolerance limits would be, and furthermore, the less the total cost of quality loss, which can be defined as the integral of $L(y)$ from $y = l - \Delta$ to $l + \Delta$.

II.2.4. Group Technology Based Design

As early as in the ó20s it was observed, that using product-oriented departments to manufacture standardized products in machine companies lead to reduced transportation. This can be considered the start of Group Technology (GT) Design.

Parts are classified and parts with similar features are manufactured together with standardized processes. As a consequence, small "focused factories" are being created as independent operating units within large facilities.

More generally, Group Technology can be considered a theory of management based on the principle that "similar things should be done similarly". In our context, "things" include product design, process planning, fabrication, assembly, and production control. However, in a more general sense GT may be applied to all activities, including administrative functions.

The principle of group technology is to divide the manufacturing facility into small groups or cells of machines. The term *cellular manufacturing* is often used in this regard. Each of these cells is dedicated to a specified family or set of part types. Typically, a cell is a small group of machines (as a rule of thumb not more than five). An example would be a machining center with inspection and monitoring devices, tool and Part Storage, a robot for part handling, and the associated control hardware.

The idea of GT can also be used to build larger groups, such as for instance, a department, possibly composed of several automated cells or several manned machines of various types.

For very large production volumes, pure item flow lines are recommended to be used. If volumes are very small, and parts are very different, a functional layout (job shop) is usually appropriate. In the intermediate case of medium-variety, medium-volume environments, group configuration is most appropriate.

GT can produce considerable improvements where it is appropriate and the basic idea can be utilized in all manufacturing environments:

- To the *manufacturing engineer* GT can be viewed as a role model to obtain the advantages of flow line systems in environments previously ruled by job shop layouts. The idea is to form groups and to aim at a product-type layout within each group (for a family of parts). Whenever possible, new parts are designed to be compatible with the processes and tooling of an existing part family. This way, production experience is quickly obtained, and standard process plans and tooling can be developed for this restricted part set.
- To the *design engineer* the idea of GT can mean to standardize products and process plans. If a new part should be designed, first retrieve the design for a similar, existing part. Maybe, the need for the new part is eliminated if an existing part will suffice. If a new part is actually needed, the new plan can be developed quickly by relying on decisions and documentation previously made for similar parts. Hence, the resulting plan will match current manufacturing procedures and document preparation time is reduced. The design engineer is freed to concentrate on optimal design.

- ***Classification***

Classification is the most important element of GT ï it refers to a logical and systematic way of grouping things based on their similarities but then sub grouping them according to their differences.

The four principles developed by Brisch for the classification of a population of parts are:

- *All-embracing*: The adopted classification system must be inclusive. It must classify all current parts within the population at hand and also allow for future product features.

- *Mutually exclusive*: Once the classification structure has been developed, a part should have only one class to be included within. The system must be mutually exclusive for achieving an unambiguous distribution of parts.
- *Based on permanent features*: The classification system must utilize only the final geometrical features of the part and not any intermediate shapes.
- *From a user's point of view*: The rules of classification must be obvious to the users, and thus should be developed based on extensive interviews with all designers within the company.

The first step in implementing a classification system is a detailed review of past products and identification of primary similarities according to, for example, overall geometry (rotational versus prismatic), presence of external features (grooves, key slots, etc.) or internal features (holes, threads, etc.). Uniformity of class sizes is desirable, but owing to increased speeds of current computers, which can search databases very quickly, it is no longer a necessity. Once a representative set of historical data has been examined, and the overall classes have been determined, the next step is examining each class for differences. This step is the most critical task in classification ï one must look for representative features that will differentiate parts and not for unique features that may never be encountered in other parts. That is, one would, actually, expect these features to be found on other past or future parts, so that when we eventually search our database we would discover past parts with similar characteristics and start our new design based on the utilization of a most similar past part ï one that has the maximum number of similar features.

A second level of features in a GT system would include ratios of diameter to length for rotational parts or ratios of maximum-dimension-to minimum-dimension for prismatic parts (but rarely actual dimensions).

Other features could be the presence of external or internal steps, specific shapes of external or internal features, presence of threads/teeth, etc. One should recall that classification at the first or subsequent levels of features may consider characteristics, such as material type, surface finish, and tolerances, which would not be very useful to geometric modeling of a part, but critical for the use of GT in process planning and assignment of parts to certain manufacturing working cells.

In conclusion to the above classification discussion, it must be noted that future users of GT can easily develop their own classification system after a careful review of the literature or past developments. There exist only a very few available commercial GT systems, and these should never be treated as turnkey systems. Classification is best achieved by expert, in-house designers.

- ***Coding***

The knowledge concerning the similarities between parts must be coded somehow. This will facilitate determination and retrieval of similar parts. Often this involves the assignment of a symbolic or numerical description to parts (part number) based on their design and manufacturing characteristics. However, it may also simply mean listing the machines used by each part.

There are four major issues in the construction of a coding system:

- part (component) population
- code detail
- code structure
- (digital) representation

One of the most widely used coding systems is OPITZ. Many firms customize existing coding systems to their specific needs.

Important aspects refer to:

- The code should be sufficiently flexible to handle future as well as current parts.
- The scope of part types to be included must be known (e.g. are the parts rotational, prismatic, sheet metal, etc.?)
- To be useful, the code must discriminate between parts with different values for key attributes (material, tolerances, required machines, etc.)

Code detail is crucial to the success of the coding project. Ideal is a short code that uniquely identifies each part and fully describes the part from design and manufacturing viewpoints. Too much detail results in cumbersome codes and the waste of resources in data collection. With too few details and the code becomes useless.

As a general rule, all information necessary for grouping the part for manufacturing should be included in the code whenever possible. Features like outside shape, end shape, internal shape, holes, and dimensions are typically included in the coding scheme.

Codes are generally classified as:

- hierarchical (also called monocode),
- chain (also called polycode),
- hybrid.

Hierarchical code structure: It can store a large amount of information within a short (length) code due to its hierarchical structure. That is, the meaning of any digit in the code is dependent on the value of the preceding digit, resulting in a tree-structure representation of a productôs characteristics (Fig.12). Hierarchical codes are efficient; they only consider relevant information at each digit. But they are difficult to learn because of the large number of conditional inferences. However, such codes could be easily decoded by computers.

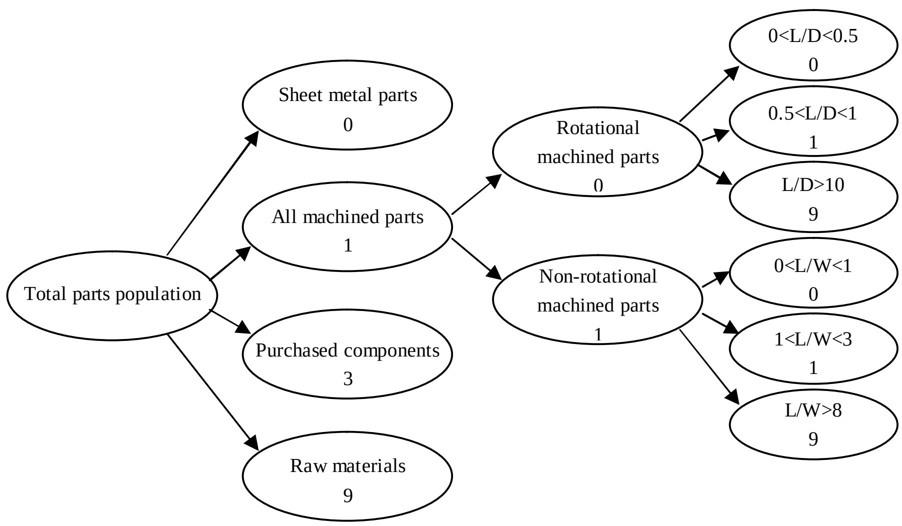


Fig.12: Hierarchical code structure

Chain code structure: In polycode, the code symbols are independent of each other. Each digit in particular location the code represents a distinct bit of information. In given Table 2, a chain-structured coding scheme is presented. Numeral 3 in the third location always means axial & cross hole no matter what numbers are specified to position 1 and 2.

Chain codes are compact and are much simple to construct and use, but they may not be as detailed as hierarchical structures with the similar number of coding digits. Consequence, only a limited amount of information can be stored, since each character is of fixed meaning. Although easily recognizable by people (in meaning), such codes can be excessive in length.

Table 2: Chain code structure

Digit position	1	2	3	4
Class of features	External shape	Internal shape	Holes	...
Possible value				
1	Shape 1	Shape 1	Axial	é
2	Shape 2	Shape 2	Cross	é
3	Shape 3	Shape 3	Axial and cross	é
é	é	é	é	é

Hybrid code structure: Mixed code is mixture of the chain code and hierarchical code (Fig.13). It retains the advantage of mono and chain both code. Therefore, most existing code system utilizes a mixed structure. Hybrid codes can be utilized for classification systems that yield group sizes of non-uniform size.

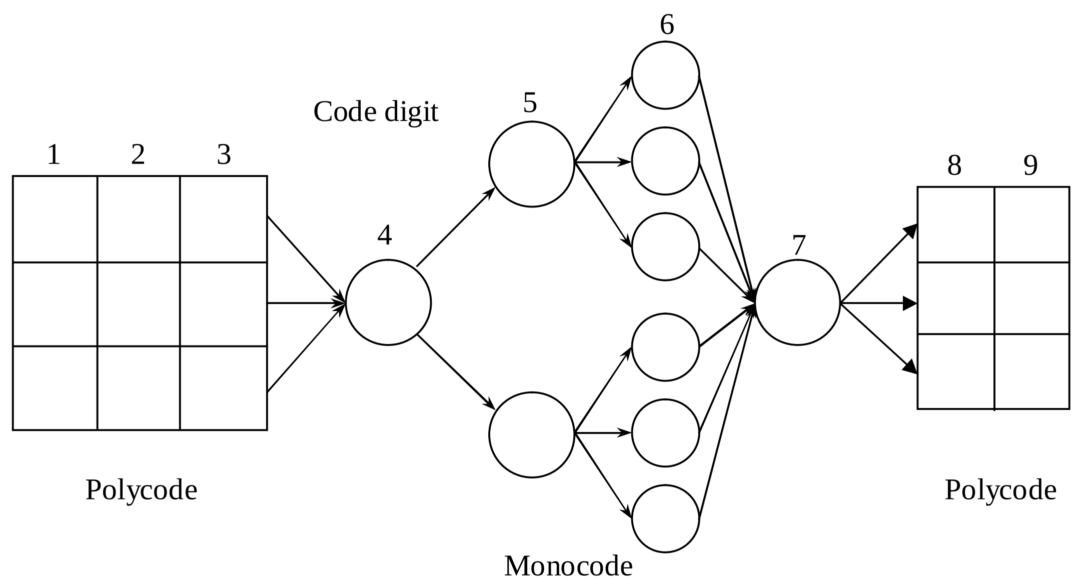


Fig.13: Hybrid code structure

- ***Implementation***

GT is based on the utilization of a classification and coding system that would allow designers to access earlier product designs based on a select set of similarities and not simply sequentially numbering these or naming them according to their functions.

Once a company has developed and installed a GT system, the first decision at hand is how to start. If it is economically feasible, a large set of past products should be coded (this step can take 1 to 6 person-months, depending on the availability of a menu-driven computer-based coding system as well as on the amount of information to be stored). An alternative would be simply to code only new parts ï which would postpone a meaningful usage of the GT system by at least one year.

With the availability of an effective database of past designs, a designer can code a new part, based on available sketchy information, and request the GT system to identify and retrieve the most similar part model from the database. The designer must subsequently decide whether it would be more economical to modify this past model rather than starting from scratch. The worst case scenario is the time wasted on the search that would, normally, take less than a few minutes. The time spent on coding the new (future) part is not wasted, since this code will be used when storing the new part in the database.

Several other points can be made at this time of discussing the use of GT in design efforts:

- Classification of a population of similar products can help manufacturers in standardizing parts or even deciding on how to modularize their products.
- If the GT system does include a component for process planning, fixture selection and other manufacturing issues, at the time of information retrieval for the most similar past product, the product development team can concurrently review these pieces of information as well and make more educated design decisions on manufacturability, etc.
- GT classification and coding systems could be used in conjunction with other methods developed for feature-based design, where CAD-based solid models are automatically analyzed for similar geometric (form) features.

II.3. Computer-Aided Design

II.3.1.What does Computer-Aided Design (CAD) mean?

Computer-aided design (CAD) is a computer technology that designs a product and documents the design's process. CAD may facilitate the manufacturing process by transferring detailed diagrams of a productôs materials, processes, tolerances and dimensions with specific conventions for the product in question. It can be used to produce either two-dimensional (2D) or three-dimensional (3D) diagrams, which can then be viewed from any angle, even from the inside looking out. A special printer or plotter is usually required for printing professional design renderings.

The concept of designing geometric shapes for objects is very similar to CAD but it is called computer-aided geometric design (CAGD).

CAD is used as follows:

- To produce detailed engineering designs through 2-D or/and 3-D drawings of the physical components of manufactured products.
- To create conceptual design, product layout, strength and dynamic analysis of assembly and the manufacturing processes themselves.
- To prepare environmental impact reports, in which computer-aided designs are used in photographs to produce a rendering of the appearance when the new structures are built.

CAD systems exist today for all of the major computer platforms, including Windows, Linux, Unix and Mac OS X. The user interface generally centers on a computer mouse, but a pen and digitizing graphic tablet can also be used. View manipulation can be accomplished with a space-mouse (or space-ball). Some systems allow stereoscopic glasses for viewing 3-D models.

Most universities no longer require classes for producing hand drawings; instead, there are many classes on different types of CAD software. Because hardware and software costs are decreasing, universities and manufacturers now train students how to use these high-level tools. These tools have also modified design work flows to make them more efficient, lowering these training costs even further.

II.3.2. Computer-Aided Design Evolution

The beginnings of CAD can be traced to year 1957, when Dr. Patrick J. Hanratty developed PRONTO, the first commercial numerical-control programming system. In 1960, Ivan Sutherland MIT's Lincoln Laboratory created SKETCHPAD, which demonstrated the basic principles and feasibility of computer technical drawing.

The first CAD systems served as mere replacements of drawing boards. The design engineer still worked in 2D to create technical drawing consisting from 2D wireframe primitives (line, arc, B spline, etc). Productivity of design increased, but many argue that only marginally due to overhead ï design engineers had to learn how to use computers and CAD. Nevertheless modifications and revisions were easier, and over time CAD software and hardware became cheaper and affordable for mid size companies. CAD programs grew in functionality and user friendliness.

3D wireframe features were developed in the beginning of the sixties, and in 1969 MAGI released Syntha Vision, first commercially available solid modeler program. Solid modeling further enhanced the 3D capabilities of CAD systems. NURBS, mathematical representation of freeform surfaces, appeared in 1989 - first on Silicon Graphics workstations. In 1993 CAS Berlin developed an interactive NURBS modeler for PCs, called NöRBS.

In 1989 T-FLEX and later Pro/ENGINEER introduced CADs based on parametric engines. Parametric modeling means that the model is defined by parameters. A change of dimension values in one place also changes other dimensions to preserve relation of all elements in the design.

MCAD systems introduced the concept of constraints that enable you to define relations between parts in assembly. Designers started to use a bottom-up approach when parts are created first and then assembled together. Modeling is more intuitive, precise and later analysis, especially kinematics easier.

CAD/CAE/CAM systems are now widely accepted and used throughout the industry. These systems moved from costly workstations based mainly on UNIX to off-the-shelf PCs. 3D modeling has become a norm, and it can be found even in applications for the wider public. Advanced analysis methods like FEM, flow simulations are a ubiquitous part of the design process. CAM systems are used for simulation and optimization of manufacturing, and numerical control (NC) code is created and loaded to NC machines.

The past of CAD has been full of unmet expectations. This continues. Some anticipate 3D modeling without flat screens or mouse pointers - a fully immersive 3D environment where modeling tools include special gloves and goggles. In the future, designing will be closer to sculpting than painting.

Up to now, 3D goggles cause nausea, immersive technologies are expensive and complex, and most designers prefer using a keyboard, stylus, and mouse.

While some of these optimistic predictions may come true, the more likely course is that the future changes will evolve in ways we do not see now. Still, some trends seem more likely to succeed and be widely adopted than others.

CAD formats will follow development in Office applications, where XML based ODF (Open Document Format) format is becoming standard. Similar standardization efforts for 3D and CAD related formats are represented by X3D.

Companies and developers will start to implement X3D import/export as default way for data exchange. This will enhance interoperability between CAD and related applications like CAE, CAM. 3D models created in CAD could be immediately presented in web browsers that will be able to display 3D models.

Increasingly 3D models are defined with physical properties, especially material and optical. Developers of industrial CAD will increasingly integrate 3D modeling with analysis tools like FEM, kinematics or flow simulations. Gap between 3D model and real objects will further narrow, 3D models will look realistically and what is even more important, they will behave as in reality. Virtual prototypes are reality in high tech environments, today. In future this principle will spread even to low end 3D applications, and will become more precise on high end ones. In some cases prototyping and tests will be skipped altogether.

CAD systems will continue in the trend of specialization. There are general purpose CADs, that can be enhanced for specific purpose and specialized CADs build upon generic engines like Open CASCADE. Examples of specialized CADs goes from OrCAD, used by electronic design engineers, Allplan for architects or ArtCAM for jewelry design. In the future we will see more task oriented and highly specialized CADs. However general purpose CADs will not disappear, they will have more functions (integrated analysis, kinematics and simulations), yet they will be easier to use.

Real time ray tracing is a resource intensive process. For example one second of high resolution movie scene takes one day and many computers. New hardware especially GPUs with parallelized 3D model processing, and software based on new algorithms can increase the speed by more than two orders of magnitude. This will bring high definition, more realistic scenes to CAD, CAE and visualization programs running on affordable computers.

Many commercial and proprietary programs have their strong open source alternatives. There is Windows and Linux, MS Office and OpenOffice, Oracle and Firebird and so on. But there is no viable strong open source competitor to commercial CAD systems like AutoCAD or SolidWorks. Yes, there are some open source CADs like BRL-CAD, but these are not widely adopted and used in industry.

In future there may be a strong open source CAD solution. It will probably be based the Open CASCADE engine. Other probable scenario is that a CAD company will start an open source project to boost its more profitable products based on same engine (for example CAM or CAE).

Development of hardware and software for both rapid prototyping and rapid manufacturing will change manufacturing, marketing and business processes. Improvements of hardware like 3D printers, laser and metal sintering will enable to produce complex parts effectively even in small series and from various materials like plastics, textile, ceramics or metal. Products will be bought in the form of license; 3D model will be downloaded from Internet and manufactured on hardware connected to computer in local store or even at home. Time needed for delivering product to market will be further decreased. It's also useful as special software for transferring CAD's files (as PRO-E, SolidWorks) to NC machines, so after modeling and drawing comes programming NC machines to make designed models as solid objects.

DPR ï Dynamic Physical Rendering is a collaborative research project between Carnegie Mellon University and Intel. This project will evolve into new representation of 3D models. Instead of 2D representations of 3D objects there will be real 3D models build in bottom-up manner. Many versatile little building blocks will form larger objects like car model according to computer program. This concept is also known as Claytronics.

Genetic programming (GP) is machine learning technique that uses an evolutionary algorithm to optimize a population of designs according to a fitness landscape determined by a design ability to perform a given computational task. GP has been successfully used for development computer programs, electronic circuits and antennas. GP technique will be used for design of complex products which consists of many parts, but limited in number of types. CAD packages will incorporate GP methods to ease, improve and speed up design of hydraulics and fluid control systems or MEMS. Later will come new manufacturing processes similar to protein creation in ribosome, where 3D protein complex structures are based on only 20 building blocks (amino acids). Computer program will serve like DNA, manufacturing hardware will serve as ribosome and one machine will be able to manufacture wide range of different products.

II.3.3. Computer-Aided Design Basics

- ***Coordinate system***

Also called *reference plane;* the coordinate system acts as a reference from which the model data is calculated. In geometry, a coordinate system is a system which uses one or more numbers, or coordinates, to uniquely determine the position of a point or other geometric element on a manifold such as Euclidean space.

The coordinates are taken to be real numbers in elementary mathematics, but may be complex numbers or elements of a more abstract system such as a commutative ring. The use of a coordinate system allows problems in geometry to be translated into problems about numbers and vice versa; this is the basis of analytic geometry.

In CAD workspace different types of coordinate systems may be used:

- *Cartesian coordinate system* – bought 2D and 3D
- *Polar coordinate system – 2D*
- *Cylindrical coordinate system – 3D*
- *Spherical coordinate system– 3D*

- ***Points***

Points are the simplest geometric entities.

If a Cartesian coordinate system is used (Fig.14), the coordinates of a point *P* are obtained by drawing a line through *P* perpendicular to each coordinate axis, and reading the points where these lines meet the axes as three numbers of these number lines. Alternatively, the coordinates of a point P can also be taken as the (signed) distances from *P* to the three planes defined by the three axes. If the axes are named *x, y*, and *z*, then the *x* coordinate is the distance from the plane defined by the *y* and *z* axes. The distance is to be taken with the + or − sign, depending on which of the two half-spaces separated by that plane contains *P*. The *y* and *z* coordinates can be obtained in the same way from the (*x,z*) and (*x,y*) planes, respectively.

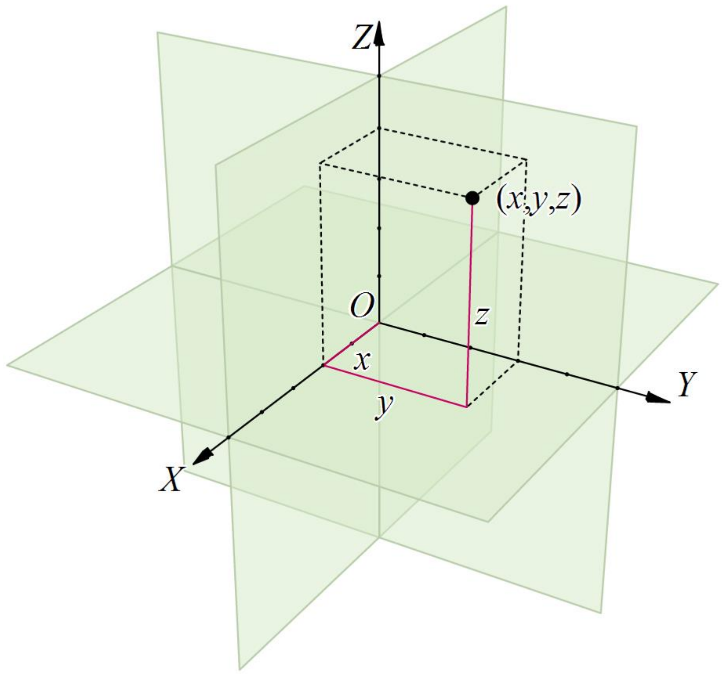


Fig.14: Cartesian coordinates of a point

In a Cylindrical coordinate system, a point position is specified by the distance from a chosen reference axis, the direction from the axis relative to a chosen reference direction, and the distance from a chosen reference plane perpendicular to the axis (Fig.15). The latter distance is given as a positive or negative number depending on which side of the reference plane faces the point. The three coordinates of a point *P* are defined as (ɟ , ű, z):

- The radial distance ɟ is the Euclidian distance from the *z* axis to the point.
- The azimuth ű is the angle between the reference direction on the chosen plane and the line from the origin to the projection of *P* on the plane.
- The height *z* is the signed distance from the chosen plane to the point *P*.

Cylindrical coordinates are useful in connection with objects and phenomena that have some rotational symmetry about the longitudinal axis, such as water flow in a straight pipe with round cross-section, heat distribution in a metal cylinder, electromagnetic fields produced by an electric current in a long, straight wire, and so on.

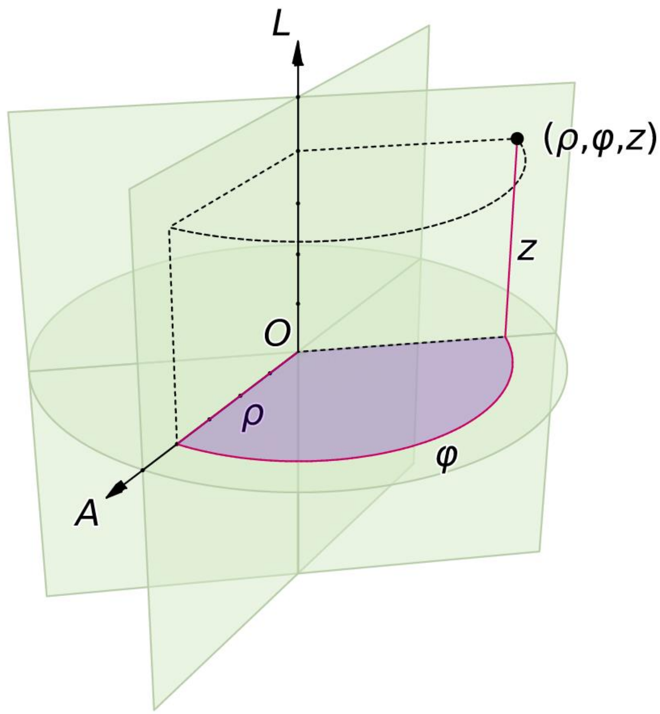
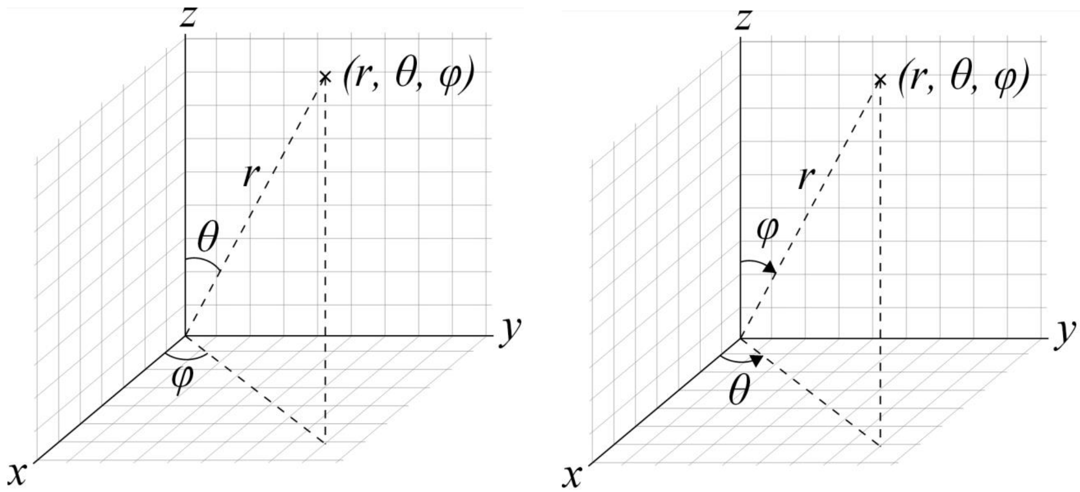


Fig.15: Cylindrical coordinates of a point

If a Spherical coordinate system is used for three-dimensional space, the position of a point is specified by three numbers: the radial distance of that point from a fixed origin, its polar angle measured from a fixed zenith direction, and the azimuth angle of its orthogonal projection on a reference plane that passes through the origin and is orthogonal to the zenith, measured from a fixed reference direction on that plane. The radial distance is also called the *radius* or *radial coordinate*. The polar angle may be called *colatitude*, and zenith angle, *normal angle*, or *inclination angle*.

The use of symbols and the order of the coordinates differ between sources. In one system frequently encountered in physics (r, θ, φ) gives the radial distance, polar angle, and azimuthal angle (Fig.16.a), whereas in another system used in many mathematics books (r, θ, φ) gives the radial distance, azimuthal angle, and polar angle (Fig.16.b). In both systems ɟ is often used instead of r. Other conventions are also used, so great care needs to be taken to check which one is being used.



(a) (b)

Fig.16: Spherical coordinates of a point

- ***Wireframe objects***

  Commonly used wireframe objects are:

- *Line*
- *Arc*
- *Circle* (full arc)
- *Ellipse*
- *Polyline* – set of connected lines and arcs
- *Rectangle* (special case of polygon)
- *Regular polygons*
- *Polygon*
- *Bézier curve* (special case of B-spline)
- *B-spline* (special case of NURBS)
- *NURBS* – Nonuniform rational B-spline

Wireframe objects are defined by control points and equation. For example a circle has center *a, b* (control point), radius *r* and equation defining set of all *x, y* circle points [7].

$$x^2 + y^2 = r^2 \qquad [7]$$

Parametric equation can be written using the trigonometric functions *sine* and *cosine* [8]:

$$x = a + r\cos t \qquad y = b + r\sin t \qquad [8]$$

where *t* is the parametric variable.

CAD systems usually use parametric versions of equation, because some wireframe objects like Beziér-spline cannot be defined by control points and simple function only. These objects are defined by many control points, vectors in control vertices that define shape and set of x, y is calculated by algorithms (instead of simple equations).

A *spline* is a sufficiently smooth polynomial function that is piecewise-defined, and possesses a high degree of smoothness at the places where the polynomial pieces connect (Fig.17).

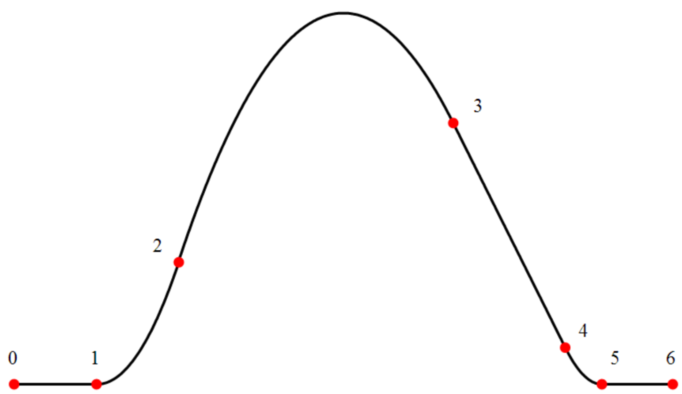


Fig.17: A quadratic spline composed of six polynomial segments

In computer graphics splines are popular curves because of the simplicity of their construction, their ease and accuracy of evaluation, and their capacity to approximate complex shapes through curve fitting and interactive curve design.

The most commonly used splines are *cubic spline*, i.e., of order 3 ï in particular, *cubic B-spline* and *cubic Bézier-spline*. They are common, in particular, in spline interpolation simulating the function of flat splines.

The term spline is adopted from the name of a flexible strip of metal commonly used by draftsmen to assist in drawing curved lines.

Non-uniform rational basis spline (*NURBS*) is a mathematical model commonly used in computer graphics for generating and representing curves and surfaces (Fig.18). It offers great flexibility and precision for handling both analytic (surfaces defined by common mathematical formulae) and modeled shapes.

NURBS are commonly used in computer-aided design (CAD), manufacturing (CAM), and engineering (CAE) and are part of numerous industry wide standards, such as ñInitial Graphics Exchange Specificationò

(IGES), ñStandard for the Exchange of Product model dataò (STEP), ñAlan, Charles, Ian's Systemò (ACIS), and ñProgrammer's Hierarchical Interactive Graphics Systemò (PHIGS). NURBS tools are also found in various 3D modeling and animation software packages.

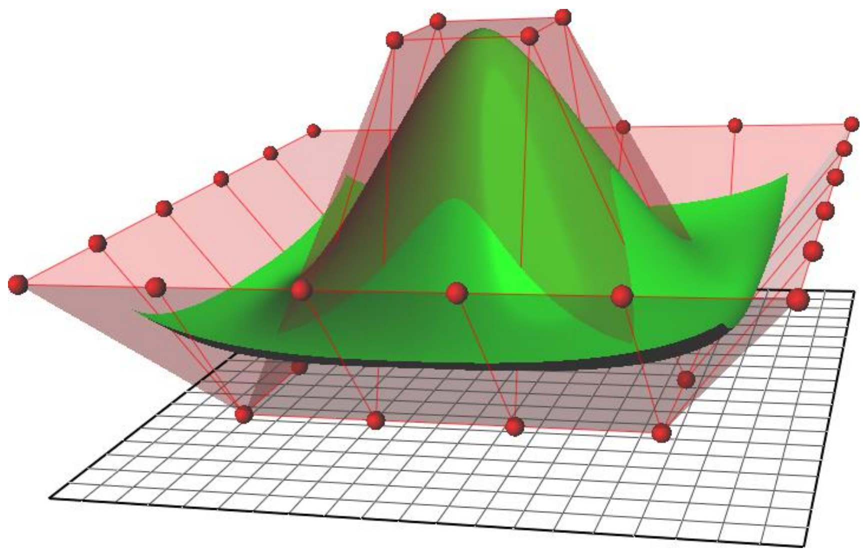


Fig.18: NURBS surface

They can be efficiently handled by the computer programs and yet allow for easy human interaction. NURBS surfaces are functions of two parameters mapping to a surface in three-dimensional space. The shape of the surface is determined by control points. NURBS surfaces can represent simple geometrical shapes in a compact form.

In general, editing NURBS curves and surfaces is highly intuitive and predictable. Control points are always either connected directly to the curve/surface, or act as if they were connected by a rubber band. Depending on the type of user interface, editing can be realized via an elementôs control points, which are most obvious and common for Bézier curves, or via higher level tools such as spline modeling or hierarchical editing.

A surface under construction is usually composed of several NURBS surfaces known as *patches*. These patches should be fitted together in such a way that the boundaries are invisible. This is mathematically expressed by the concept of geometric continuity.

Higher-level tools exist which benefit from the ability of NURBS to create and establish geometric continuity of different levels:

- *Positional continuity* ï holds whenever the end positions of two curves or surfaces are coincidental. The curves or surfaces may still meet at an angle, giving rise to a sharp corner or edge and causing broken highlights.
- *Tangential continuity* ï requires the end vectors of the curves or surfaces to be parallel and pointing the same way, ruling out sharp edges. Because highlights falling on a tangentially continuous edge are always continuous and thus look natural, this level of continuity can often be sufficient.
- *Curvature continuity* ï further requires the end vectors to be of the same length and rate of length change. Highlights falling on a curvature-continuous edge do not display any change, causing the two surfaces to appear as one. This can be visually recognized as ñperfectly smoothò. This level of continuity is very useful in the creation of models that require many bi-cubic patches composing one continuous surface.

NURBS curves and surfaces are useful for a number of reasons:

- They are invariant under affine transformations: operations like rotations and translations can be applied to NURBS curves and surfaces by applying them to their control points.
- They offer one common mathematical form for both standard analytical shapes (e.g., conics) and free-form shapes.
- They provide the flexibility to design a large variety of shapes.
- They reduce the memory consumption when storing shapes (compared to simpler methods).
- They can be evaluated reasonably quickly by numerically stable and accurate algorithms.

- ***Surfaces***

Surfaces can be understood as parts of the outer shape of an object or as idealized sheet metal with zero thickness. Surface can be represented in several ways, but the most common is as a parametric surface.

There are different types of surfaces:

- *Regular surfaces* (or canonical) ï include surfaces of revolution such as cylinders, cones, spheres, and tori, and ruled surfaces (linear in one direction) such as surfaces of extrusion.
- *Surface mesh*
- *Facet surface*

- *Voxel surface*
- *Freeform surfaces* (usually NURBS ï Fig.18) allow more complex shapes to be represented via freeform surface modeling.

Surface modeling is a natural extension of curve representation and an important step toward solid modeling.

- ***Solid modeling***

A solid represents a complete physical body, usually part that can be manufactured from one piece of material. Solid objects have a volume and other physical and optical properties (mass, density, opacity, etc).

Most common solid modeling techniques used by CAD systems are:

- *primitive instancing and sweeping*,
- *construction*
- *boundary representation* (B-rep or BREP).

Primitive instancing refers to the scaling of simple geometrical models (primitives) by manipulating one or more of their descriptive parameters, for example, elongating a cylinder, changing the dimensions of a rectangular, prism, etc.

Geometric primitives can play an integral role in feature-based design, where a set of features (forms) are combined to generate a more complex model. Primitives such as *Box, Wedge, Cylinder, Cone, Sphere, Torus* can be combined through Boolean operators as *Union*, *Subtraction* or *Intersection* for constructive solid geometry modeling.

Due to their simplicity, most geometric primitives can be generated by a sweeping process (*extrusion*), where a surface is either rotated around one axis or translated along it (Fig.19).

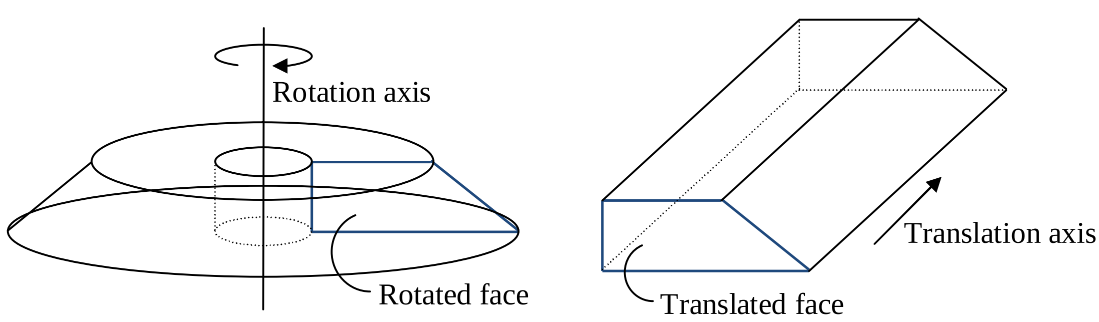
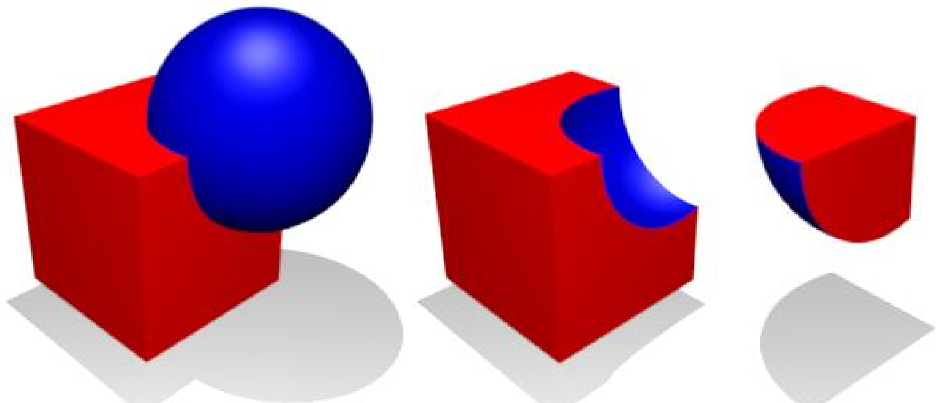


Fig.19: Rotational and translational extrusion of a face

Constructive solid geometry (CSG) is a technique used in solid modeling. Constructive solid geometry allows a designer to create a complex surface or object by using Boolean operators such as *union*, *intersection* and *difference* (*complement*) to combine objects (Fig.20). Often CSG presents a model or surface that appears visually complex, but is actually little more than cleverly combined or decombined objects.



Union Complement Intersection

Fig.20: Boolean operations

In 3D computer graphics and CAD CSG is often used in procedural modeling.

One of the advantages of CSG is that it can easily assure that objects are "solid" or water-tight if all of the primitive shapes are water-tight. This can be important for some manufacturing or engineering computation applications. By comparison, when creating geometry based upon boundary representations, additional topological data is required, or consistency checks must be performed to assure that the given boundary description specifies a valid solid object.

A convenient property of CSG shapes is that it is easy to classify arbitrary points as being either inside or outside the shape created by CSG. The point is simply classified against all the underlying primitives and the resulting boolean expression is evaluated. This is a desirable quality for some applications such as collision detection.

CSG-based solid models are represented as tree (or graph) structures. The leaves of the graph are the primitives, while the nodes that connect the branches are the Boolean operations applied on the individual (leaves) primitives (Fig.21).

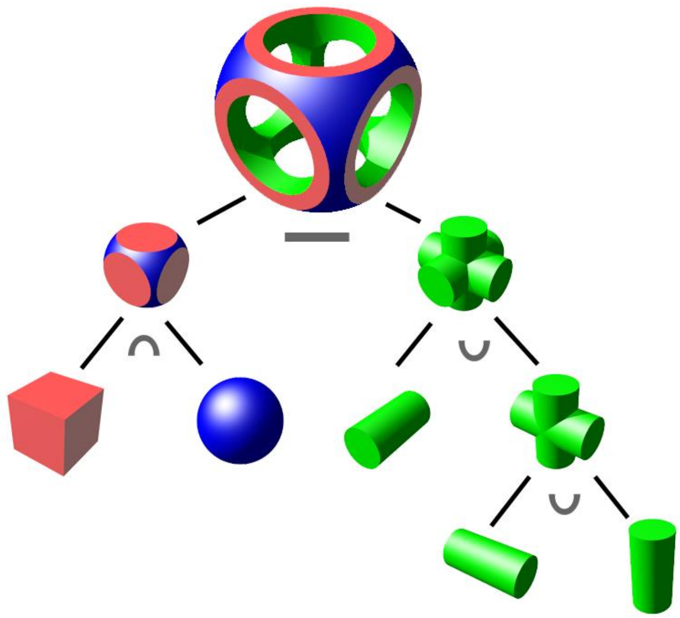


Fig.21: Binary trees representation of CSG objects

Boundary representation (B-Rep) models represent a solid indirectly by a representation of its bounding surface. A B-Rep solid is represented as a volume contained in a set of faces together with topological information which defines the relationships between the faces. Because B-Rep includes such topological information, a solid is represented as a closed space in 3D space. The boundary of a solid separates points inside from points outside of the solid. B-rep models can represent a wide class of objects but data structure is complex, and it requires a large memory space. A very simple B-rep model constructed using 6 faces is shown in Fig.22.

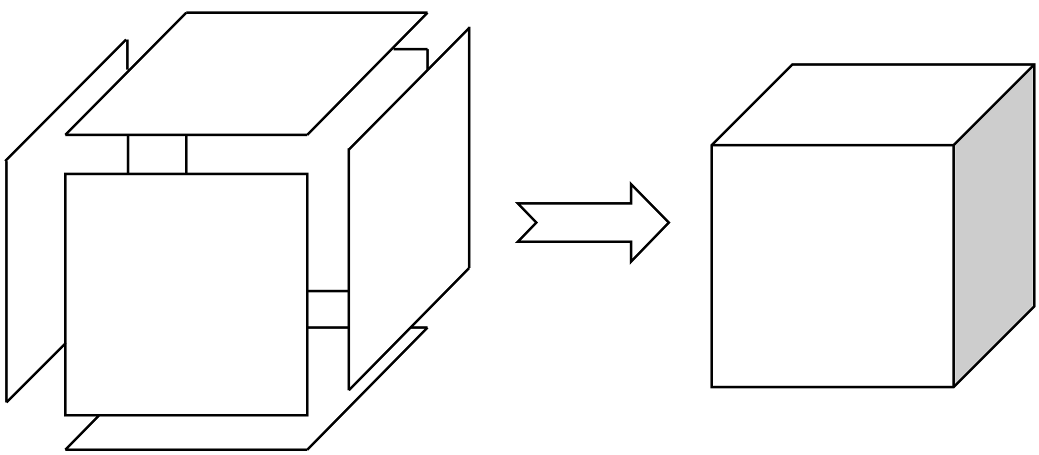


Fig.22: A simple B-rep model constructed using 6 faces

Normally a face is a bounded region of a planar, quadratic, toroidal, or sculptured surface. The bounded region of the surface that forms the face is represented by a closed curve that lies on the surface. A face can have several bounding curves to represent holes in a solid. The bounding curves of faces are represented by edges. The portion of the curve that forms the edge is represented by two vertices.

A B-Rep model has to fulfill the following conditions:

- The set of faces forms a complete skin of the solid with no missing parts, and faces do not intersect each other except at common vertices or edges;
- The boundaries of faces do not intersect themselves.

Boundary representation can be divided in three classes:

- *Facetted* ï In facetted B-Rep, a solid is bounded by planar surfaces. Only points, planes and planar polygons are necessary and are implicitly represented by their vertex points.
- *Elementary* ï The surfaces included in elementary B-Rep are planar, quadric, and toroidal surfaces. The bounding curves of the faces are lines, conics, or 4^{th} order curves.
- *Advanced B-Rep* ï In advanced B-Rep, the surfaces include also spline surfaces (B-Spline, Bézier, NURBS, etc.) in addition to elementary B-Rep. The bounding curves are spline curves.

Faces, edges, and vertices, and the related geometric information form the basic components of B-Rep models. The geometric information contains the face and edge equations (or information to compute them), and vertex coordinates. The topology contains the information on the relation of the components, i.e. how the faces, edges and vertices are connected together. In facetted B-Rep, all edges are straight line segments. Therefore faces can be represented as polygons and each polygon as a set of coordinate values x, y and z. The data structure in this case is simple and easy to implement. Facetted approximation of more sophisticated B-Rep models are normally used for generation of graphical output since it is cheaper in terms of computations.

Due to the complexity of the construction of the B-Rep models, it is not trivial for a designer to build correct B-Rep models directly. The designer needs a sufficient collection of more convenient and efficient solid description methods. For a B-Rep designer, it is not easy to implement a textual user interface. However, it is possible to create description languages that are based on a CSG input.

A common solution is to construct B-Rep models through a conversion from CSG in which the operations are limited to Boolean operations. For that purpose, the B-Rep designer must include algorithms for creating B-Rep models from the CSG primitives, and computing Boolean operations on these models (i.e. boundary evaluation).

To compute Boolean operations for B-Rep models is expensive and numerical problems may occur. Sometimes the boundary evaluation is not trivial or even impossible to perform since some CSG models have no convenient representations in B-Rep. For example, a CSG solid may be constructed as a Boolean subtraction of two cylinders where the cylinder to be subtracted is inside the other cylinder and touches it at one side. The resulting B-Rep model would have four surface edges at that point where only two are allowed.

B-Rep is used in the automotive and airplane industries since it allows having descriptions of the surfaces to be used, for example, in making the presses which are to form the sheets for the wings, doors etc.

- ***Feature-Based Design***

Features can be viewed upon as information sets that refer to aspects of form or other attributes of a part, in such a way that these sets can be used in reasoning about design, performance and manufacture of the part or the assemblies they constitute. A product model can be built by using (design) features; this is known as *design by features* or *feature-based modeling*

From a manufacturing engineering point of view, features can be seen as specific geometric shapes on a part that can be associated with certain fabrication processes. Thus it has been long advocated that if these features were highlighted during the modeling phase of a productǿs design process, in the subsequent production-planning phases, engineers could take advantage of this information in accessing historical data regarding the production of these features. Naturally, the engineers would have to be provided with material, tolerance, and other pertinent data to complement the identified geometric (feature) information in reaching production decisions.

Features have been commonly classified by J. J. Shah and others as: form, material, precision and technological features.

Form features identify geometric elements on the main body of a part (holes, slots, ribs, bosses, etc.).

Material features capture material-composition and heat-treatment information.

Precision features refer to tolerance data.

Technological features represent information related to the productôs expected performance parameters.

The objectives of design by features, as mentioned above, are:

- To increase the efficiency of the designer during the geometric-modeling phase,
- To provide a bridge (mapping) to engineering-analysis and process-planning phases of product development.

The former can be achieved by providing designers with a library of features from which they can pick and place on the main configuration (body) of a part, or allowing them to extract (identical or similar) features from previous solid models of parts without an extensive feature library.

Current numerical CAD packages offer (limited) design-by-features capabilities. As is the case of many commercial CAD systems, form features can be individually modeled by the user explicitly using a B-Rep modeler (yielding unambiguous topological relationship information) or implicitly using a CSG modeler (yielding a tree representation of corresponding primitives and Boolean operators). Any attempt to generate a universal set of features must cope with the problem of database management storage and retrieval of form features, whose numbers may become unmanageable.

A potential tool in dealing with such a difficulty would be the utilization of a logical classification and coding system for the form-feature geometries, such as a GT-based system. In working with such a feature-based design system, the user would require the CAD system to search through the database of previous designs, identify similar features, and extract them for use in the modeling of the part at hand.

However, research in the field is still going on, the emphasis being on automatic recognition and identification of features from partsô solid models (primarily B-Rep models).

Automatic feature recognition normally refers to the examination of partsô solid models for the identification of features that have been predefined. The primary objective is not feature extraction but identification of the existence of a specific feature for the extraction of, for example, pertinent manufacturing information. There have been numerous techniques proposed in the literature for the subsequent phase of feature extraction and use in solid modeling. However, one may question the need for the extraction of the geometric information of an already known entity. Thus recently there have been research efforts in developing extraction methods that would examine partsô solid models for the existence of geometric features, which have not been predefined, and extract them. Such features could then be classified and coded for possible future use in a GT-based CAD system. These features would continue to be part of the overall solid model of the part but be extractable in the future based on a user-initiated search for the most similar feature in the database via a GT code.

The two most important feature-recognition categories to date are:

- *graph matching* ï normally, refers to topological matching in terms of the connectivity of faces that define form features within a B-Rep solid model.
- *volume decomposition* ï features are defined as volumes and decomposed from the partôs solid model by subtraction (of primitives), yielding a tree structure, the nodes of which indicate Boolean operators (as in CSG), and the extracted features are the lowest leaves of the tree. Predefined features are then compared and matched to these volumes (features).

II.4. Computer-Aided Engineering

II.4.1. Introduction to CAE

Computer-aided engineering (CAE) is the broad usage of computer software to aid in engineering analysis tasks. It includes *Finite Element Analysis* (FEA), *MATLAB Simulink*, *MotorCAD*, and other optimization programs.

Software tools that have been developed to support these activities are considered CAE tools. CAE tools are being used, for example, to analyze the robustness and performance of components and assemblies. The term encompasses simulation, validation, and optimization of products and manufacturing tools. In the future, CAE systems will be major providers of information to help support design teams in decision making.

In general, there are three phases in any computer-aided engineering task:

- *Pre-processing* ï defining the model and environmental factors to be applied to it;
- *Analysis solver* ï usually performed on high powered computers (requiring great computational resources);
- *Post-processing of results* ï using visualization tools

This cycle is iterated, often many times, either manually or with the use of commercial optimization software.

As previously presented engineering design starts with identifying customer requirements and developing the most promising conceptual product architecture to satisfy the needs. This stage is often followed by a finer decision making process on issues such as product modularity as well as initial parametric design of the product, including its subassemblies and parts. The concluding phase of design is engineering analysis and prototyping, facilitated through the use of computing software tools. Consequence, students are taught many analytical tools for solving closed-form engineering analysis problems as well as numerical techniques for solving problems that lack closed-form solution models. They are, however, often reminded that the analysis of most engineering products requires approximate solutions and furthermore frequently need physical prototyping and testing under real operating conditions owing to our inability to model all physical phenomena analytically.

The objective of engineering analysis can therefore be noted as the optimization of the selected design. The objective function of the optimization problem would be maximizing performance and/or minimizing cost. The constraints would be those set by the customer and translated into engineering specifications and/or by the manufacturing processes to be employed. These would, normally, be set as inequalities, such as a minimum life expectancy or a maximum acceptable mechanical/electrical/magnetical/thermal stress. The variables of the optimization problem are the *geometric parameters* of the product (dimensions, tolerances, etc.) as well as *material properties*.

A careful design-of-experiments process must be followed, regardless whether the analysis and prototyping process is to be carried out via numerical simulation or physical testing, in order to determine a minimal set of optimization variables. The last step in setting the analysis stage of design is selection of an algorithmic search technique that would logically vary the values of the variables in search of their optimal values. The search technique to be chosen would be either of a combinatory nature for discrete variables or one that deals with continuous variables.

Next, most common analysis tools used in electrical engineering will be reviewed.

II.4.2. Finite-Element Modeling and Analysis

The finite-element method provides engineers with an approximate behavior of a physical phenomenon in the absence of a closed-form analytical model. The quality of the approximation can be substantially increased by spending high levels of computational effort (CPU time and memory). In this method, objects geometries are represented as a collection of (finite) elements connected to each other at nodal points (nodes). Variations within each element are approximated by simple functions to analyze variables, such as flux density, displacement, temperature, velocity, etc. Once the individual variable values are determined for all the nodes, they are assembled by the approximating functions throughout the field of interest.

Although approximate mathematical solutions to complex problems have been utilized for a long time (several centuries), the finite-element method (as it is known today) dates only back several decades. The first attempts at using the finite-element method were for the analysis of aircraft structures. In the past several decades, however, the method has been used in numerous engineering disciplines to solve many complex problems:

- *Mechanical engineering*: stress analysis of components (including composite materials); fracture and crack propagation; vibration analysis (including natural frequency and stability of components and linkages); steady-state and transient heat flow and temperature distributions in solids and liquids;

and steady-state and transient fluid flow and velocity and pressure distributions in Newtonian and non-Newtonian (viscous) fluids.

- *Electrical engineering*: a large number of functionalities, including extended multi-parametric analysis, advanced electrical circuit coupling and kinematic coupling; suitable for magnetic, electric and thermal fields, magnetic/dieletric/thermal coupling, mechanical coupling, multi-physics coupling, static, harmonic and transient analysis, parameterized analysis, external circuit connections; being the right tool for the analysis, design and optimization in following applications: rotating machines, linear actuators, transformers & inductances, induction heating devices, sensors, high voltage devices, cables, electromagnetic compatibility, non destructive testing, and many others.
- *Aerospace engineering*: stress analysis of aircraft and space vehicles (including wings, fuselage, and fins); vibration analysis; and aerodynamic (flow) analysis.
- *Biomedical engineering*: stress analysis of replacement bones, hips and teeth; fluid-flow analysis in blood vessels; and impact analysis on skull and other bones.

The finite-element modeling and analysis for the above-mentioned and other problems is a sequential procedure comprising the following primary steps:

- *Geometry building and mesh generation (discretization);*
- *Physical proprieties assignment;*
- *Problem solving;*
- *Post-processing and results analysis.*

- ***Geometry building and mesh generation (discretization):***

In electromagnetic problems analysis, it is necessary to model both the device and the surrounding air. In fact, the quantities studied in electromagnetics (electric fields, magnetic fields), are not considered null in air or in a vacuum, contrary to other physics disciplines, mechanics, for example, where air is not taken into account. But, the finite element method is based on the subdivision of the entire study domain in a finite number of sub domains of finite size. The physical problem is governed by a differential equation with partial derivatives that should be satisfied on all the points of a domain. To ensure the uniqueness of the solution, boundary conditions on the outer edges must be imposed. Thus, to solve a problem with the finite element method, it is necessary to set limits on the device model, i.e. to define the limits or boundaries of the domain, and to impose boundary conditions on the edges, i.e., to define the values of the state variable (potential, temperature) on the boundaries of the domain.

As the finite element method requires limits on the problem region, while the electromagnetic phenomena are unlimited; *open domains cannot be modeled by the finite element method*, because it is impossible to subdivide an infinite domain into a finite number of finite sub-domains. To offset this contradiction, different methods can be used. The first method (the truncation method) consists of closing the study domain with an outer boundary sufficiently far away from the device so as not to interfere with the results. The second method consists of using a transformation that converts the open domain into a closed domain.

In the first case, the device is placed inside an *air–filled box*, and infinity is approximated by a closed and remote truncation boundary. The size of the air-filled box is adjusted so that the effects of the truncation boundary approximation can be neglected. The user must determine the quantity of air to model around the device, i.e., to evaluate the distance at which the computed fields become negligible.

The truncation method has certain disadvantages: relatively high cost in terms of numbers of unknowns and negligible field values near the truncation boundary. To compensate for these disadvantages, a second method consists of using a transformation that converts the open domain into a closed domain. The basic idea is to transform the open domain into a closed domain because the open domain cannot be meshed.

The initial space is decomposed into two domains: closed interior domain, and an open exterior domain. The initial space, with open borders, is transformed into a final space with closed borders, in the following way: the interior domain remains unmodified, while the exterior domain is linked to a closed domain through a spatial transformation T. In the terminology of the software, using a transformation to model an infinite domain is called the *infinite box* technique or method. The exterior domain (infinite) is linked to an image domain (called the infinite box) through a space transformation. The use of the infinite box implicitly assumes a null field at infinity. The dimensions of the infinite box are defined by the user. This requires a certain experience because there is no general rule. The mesh and the size of the infinite box must take into account the phenomena studied, and the computations to be performed. So, it is recommended to parameterize the dimensions of the infinite box to adjust its size during the meshing.

A preliminary analysis of the device may highlight the presence of repetitive patterns (*periodicities*) or *symmetry planes*. Under these conditions, it is possible to reduce the study domain as follows: representation of a fraction of the device or assignment of appropriate boundary conditions on the model boundaries that reflect the periodicity property or symmetry conditions.

The consequences of a reduction of the device model are a simplification of the geometrical description and a reduction of the finite element problem size (and thus the file size). The rationale for reducing the problem size is the reduction of the computation time. The computation time is roughly proportional to the square of the number of unknowns.

The geometry building module in FEM is of *boundary type*, which means that a volume is described by the bordering faces and a face is described by the bordering lines and a line is described by points. The geometry is created in ascending way: first the points, then the lines, and finally the faces and the volumes. The points and lines are defined manually (input of point coordinates, selection of the ends of the lines, etc.). The faces and the volumes are automatically identified and created (algorithms of automatic construction). The algorithms of automatic construction of faces and volumes are powerful, but difficulties can however arise, being determined either by a ñbadò geometrical description (problems of intersection or superposition of entities), or by numerical problems. Construction problems may occur in the presence of overlapping points, or lines of null length; intersection or superposition of lines; or intersection of faces. Numerical problems of recognition of faces or volumes can also occur in the presence of faces characterized by too important numerical waves.

A powerful tool of geometry building module is the *parameterization* of the geometry. It is possible to parameterize: dimensions of work-pieces as well as relative displacements of pieces (variable air-gap). A geometrical object can be parameterized on one hand, using the *geometrical parameters*, on the other hand, using the *local coordinate systems* (coordinate systems defined with respect to a reference coordinate system). Each time a geometrical entity is modified; all the entities depending on this geometrical entity are automatically reevaluated through the database tools. Modifying a parameter or a coordinate system entails the modification of the points, then of the lines, and then of the faces and volumes that are attached to this parameter.

To facilitate furthermore the geometrical description of a problem, various tools for automatic construction can be used. They allow the duplication of repetitive geometrical patterns, or the fast construction of structures presenting symmetries; using *propagation* or *extrusion*. The basic idea is to automatically generate new objects, based on the objects already created (points, lines and faces) by using *transformations*; transformations are geometrical functions of *translation*, *rotation*, or *affinity type*.

The mesh is a subdivision of a domain into sub-domains called elements. This is performed by a special tool named *mesh generator.* Different types of algorithms are used by mesh generators in order to accomplish the subdivision of a domain.

The Delaunay or *automatic mesh algorithm* is fairly general: it creates *triangular elements* on all the surfaces defined by their meshed outlines and *tetrahedral elements* on all the volumes defined by their meshed surface contours (Fig.23).

Triangle Tetrahedron

Fig.23: Automatic mesh algorithm

Topological mesh or mapped mesh generator (Fig.24) allows the mesh of rectangular faces with *rectangles* (or quadrangular elements) and volumes such as parallelepiped with ñ*brick*sò (or hexahedron elements). With the mapped mesh algorithm, the outline of a surface is divided into four lines, each one meshed so that two opposite lines have the same number of elements. The surface to be meshed is thus topologically equivalent to a rectangle. For the mapped mesh of a volume, the volume is topologically equivalent to a parallelepiped.

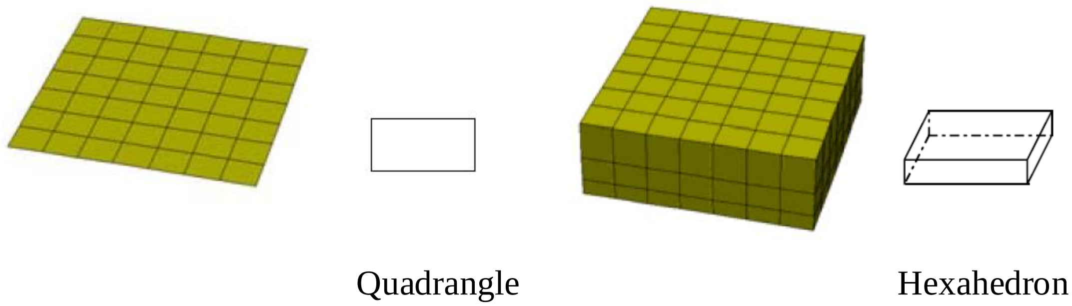


Fig.24: Topological mesh or mapped mesh generator

Copy mesh or *linked mesh* generator allows you to impose the same mesh on faces linked by a geometrical transformation (Fig.25). This mesh generator can be used only for faces.

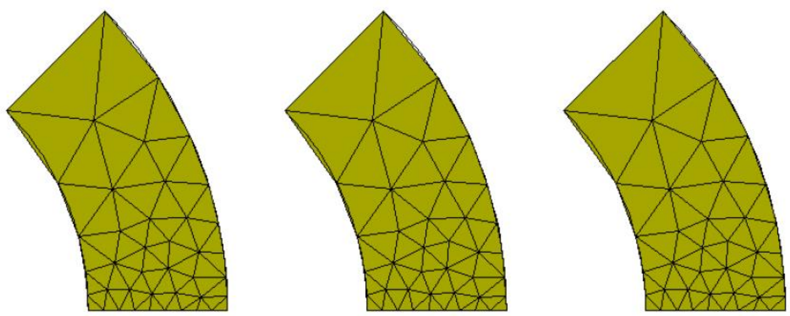
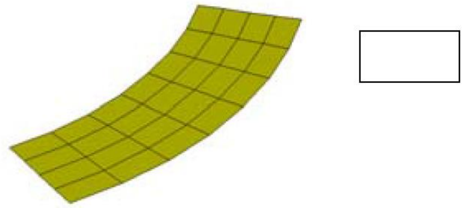
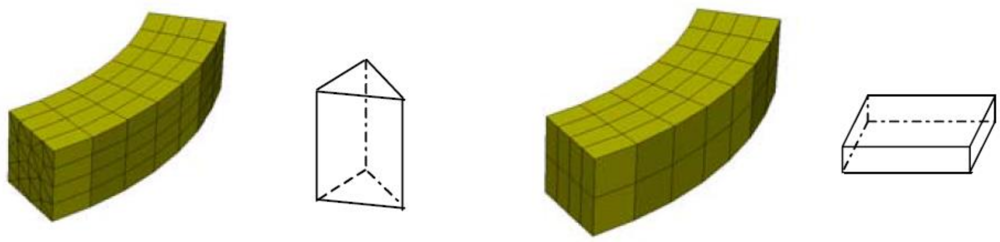


Fig.25: Linked mesh generator

Mesh by "movement" or *by extrusion* generates a surface or volume mesh in layers on domains obtained by extrusion. This mesh is potentially anisotropic and the volume elements are *prisms* or *hexahedrons*, depending on the mesh of the base faces (*triangles* or *rectangles*). With the extrusive mesh algorithm, a meshed line can be ñmovedò or shifted along a meshed path (Fig.26.a) ï the movement must be simple that is, translation or rotation. Thus a mesh using quadrangles is generated. The same method is used to mesh volumes by moving or shifting a meshed surface (Fig.26.b).



(a) rotation of a line



Pentahedron Hexahedron

(b) rotation of a face

Fig.26: Extrusion mesh generator

The mesh on sub-domains or *the mixed mesh* is a combination of the previous mesh generators applied on sub-domains. The main difficulty with the mixed mesh is ensuring the coherence of the mesh on the interfaces between the sub-domains: the mesh on both sides of the sub-domain interfaces should be identical. This conformity is not easy to obtain in 3D, when different mesh algorithms are used on neighboring sub-domains. To ensure the coherence of the mesh on sub-domain interfaces, the 3D mixed mesh generator creates pyramidal volume elements that ensure the proper connection between triangular faces and rectangular faces (Fig.27).

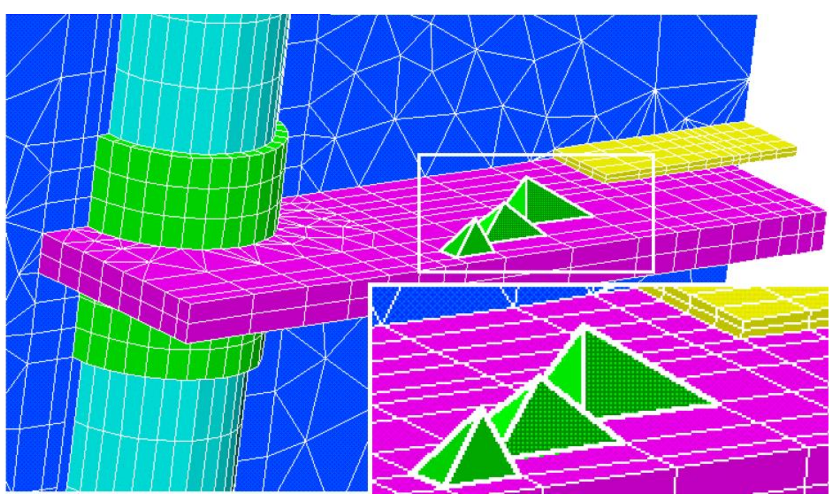


Fig.27: Mixed mesh generator

The finite element based computation allows the approximation of state variables such as scalar or vector potentials, temperature, etc. and of derived quantities, such as magnetic field and induction, magnetic flux density, electric field, thermal flux density, etc. The quality of the approximate solution depends on the mesh. Thus, the quality of the solution depends on the number and the dimensions of the finite elements, the interpolation functions in each element, which can be 1st, 2nd order polynomial functions, and on the continuity conditions imposed on the sub-domain boundaries.

In terms of the geometry, a volume element is characterized by its *vertices*, *edges* and *faces* (Fig.28). In terms of the finite element computation, there are use *nodal elements* (computation on element nodes) and *edge elements* (computation on element edges).

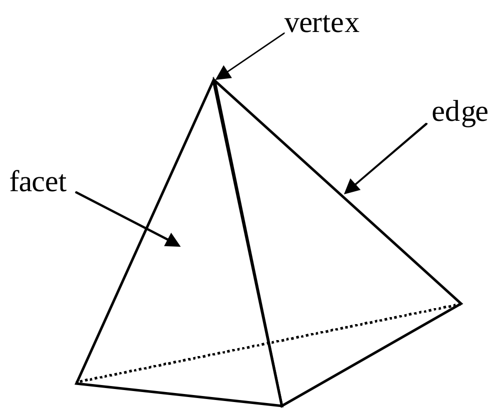


Fig.28: Characteristics of a volume element

Different types of finite elements are available to the user, called 1st order elements or 2nd order elements. Using 1st order elements: the potentials are approximated linearly and the fields derived from the potentials are constant. Using 2nd order elements: the potentials are approximated quadratically and the fields are approximated linearly.

To generate a valid mesh, there are strategies and rules that facilitate the mesh of particular geometries, and a certain number of rules to follow to mesh rotating and translating air-gaps. During the solving process, these regions are rebuilt for each change in the position of the moving part.

The mesh quality is evaluated automatically and displayed for the user knowledge. If the desired quality is achieved, the mesh will be accepted, otherwise an adjustment process will be started.

- ***Physical proprieties assignment:***

The magnetical, electrical and thermal phenomena are described by different equations: Maxwellôs equations, heat equation and material constitutive laws. The simultaneous numerical integration of all these equations is difficult to achieve because of its complexity and of the volume of computations to be carried out. For this reason, several physical applications can be performed, each one allowing the solving of a given type of problem described by an equation, by the operating hypothesis and by the boundary conditions. Thus, the concept of physical application regroups information that concerns: the solved equation and the solving mode of this equation (model, formulations, approximations, etc.); the operating hypotheses (characteristics of the material media and the material behavior, characteristics of the sources, etc.) and the boundary conditions (infinite box, conditions of symmetries and/or periodicity, other conditions imposed by the user).

The basic applications can be regrouped in three categories:

- *magnetic applications*
- *thermal applications*
- *electrical applications*

To these applications, the applications related to a strong coupling between the magnetic or electric applications, and the thermal ones are to be added. It is possible to distinguish the following two categories:

- *magneto-thermal applications*
- *electro-thermal applications*

The previously defined applications can be classified depending on the states of the studied fields into:

- *static applications* that treat static or steady state phenomena in devices where the field sources are time independent;
- *transient applications* that treat variables or transient phenomena in devices where the field sources are time dependent;
- *steady state AC applications* for devices where the time variation of the field sources is sinusoidal.

The choice of an application depends on the problem type and on the results the user is interested in.

A real device consists of a certain number of components (magnets, magnetic poles, magnetic cores, coils, etc.) that have their own particular physical characteristics (hard magnetic material, soft magnetic material, current, etc.). Any component of a device, with a more or less complex geometry, can be described by several volumes. Thus, it is necessary to regroup the different volumes in the same region and to associate the physical properties of the related component to this region.

A region is a group of geometric elements of the same type, having the same physical properties. From a geometric point of view we can distinguish four types of regions, corresponding to the four types of geometric entities: *points*, *lines*, *faces*, *volumes*. From a physical point of view we can distinguish two types of regions: *material regions* (magnetic part, conducting part, air-gap, etc.) and regions known as *non-material regions* (normal field crossing a face, imposed potential on a line, etc.).

Physical description process includes different steps that depend, in part, on the physical application used. Generally, it is possible to distinguish the following stages:

- *Choice of the physical application,*
- *Definition of boundary conditions on the external boundaries of the field computation domain (symmetries/periodicities),*
- *Creation or import of materials,*
- *Creation of materials regions and assignment of these regions to geometric entities,*
- *Creation of regions known as non material regions and assignment of these regions to geometric entities.*

The materials utilized generally have an anisotropic, nonlinear, hysteretic behavior, and the corresponding material properties can also depend more or less strongly on other physical quantities, for example on temperature or frequency. The behavior laws can therefore be very complex if we wish to get a very accurate representation of the materials. Generally, it is not possible to express the complexity of a behavior law into one single model, which would simultaneously take into consideration the various aspects previously mentioned. Indeed, in order to carry out the numerical simulation of a device with the given models of materials, one must take into consideration a certain number of requirements, such as: the possibility of evaluating all the model parameters within a reasonable time interval and the possibility of carrying out the field computations utilizing these models, by the available numerical tools and within a reasonable time interval. Therefore, the same material can be modeled in several ways, the choice depending on the studied phenomena and the operation conditions.

The numerical analysis of electrical devices can be restricted by the complexity of the power supply. It may be difficult to get the values of the supplying voltages and/or currents of the different electrical circuits of the device. By introducing the electrical equations directly into the software of magnetic field computation, the *field-circuit coupling* allows the treating of electrical circuits and of their supply circuit. It is referred to field-circuit coupling or coupling with the circuit equations, whenever the conductors of the finite elements domain are supplied by an external electrical circuit and the solutions of the electrical circuit and of the magnetic field are not independent of one another.

The mathematical methods of coupling depend on the one hand, on the formulation used for the magnetic field computation, on the other hand, on the method of analysis of the electrical circuit. In all cases, the magnetic field equations and the circuit equations are solved simultaneously.

The conductors related to the field ï A.C. circuit coupling are of two types:

- *solid conductors* (with the shape of bars or plates) are characterized by a value of the skin depth comparable to or smaller than the dimensions of the conductor cross-section. The density of supplied or induced (eddy) currents is non-uniform in the cross-section of such conductors;
- *stranded conductors* are characterized by a value of the skin depth much greater than the dimensions of the conductor cross-section and, as a consequence, by an almost uniform distribution of the current in the conductor cross-section.

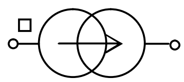
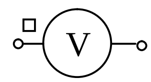
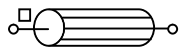
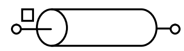
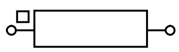
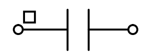
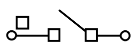
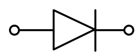
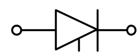
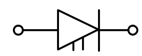
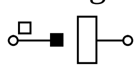
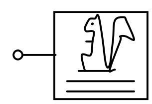
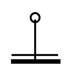
An electrical circuit comprises various components that can be:

- *generic components*, such as: sources (of current or of voltage), passive components (resistors, coils, capacitors), semi-conductors (switches, diodes, thyristors, GTO);

- *specific components*, concerned by the field-circuit coupling, such as: solid conductors and stranded conductors.

The different types of components available for the description of an electrical circuit, as well as their graphical representation, are shown in Table 3.

Table 3: Electrical circuit components

<table>
<tr><td>Sources</td><td colspan="6">Voltage
</td><td colspan="6">Current
</td></tr>
<tr><td>Fieldï circuit coupling components</td><td colspan="6">Stranded conductor
</td><td colspan="6">Solid conductor
</td></tr>
<tr><td>R, L, C components</td><td colspan="4">Resistor
</td><td colspan="4">Coil
</td><td colspan="4">Capacitor
</td></tr>
<tr><td>Switches and semi-conductors components</td><td colspan="3">Switch
</td><td colspan="3">Diode
</td><td colspan="3">Thyristor
</td><td colspan="3">GTO
</td></tr>
<tr><td>Rotating machine components</td><td colspan="6">Brush-segment
</td><td colspan="6">Squirrel cage
</td></tr>
<tr><td>Ground</td><td colspan="12"></td></tr>
</table>

The components are described by their electrical behavior. For the generic components it is the current-voltage characteristic, i.e. the relation between the voltage at the component terminals and the current that flows through the component. For the specific components it is the differential equation linking the magnetic potential, the electric potential, the current and the voltage.

The topology of an *electrical circuit* (or of an electrical network) consists of an assembly of *nodes* and *branches* that contain one or more series connected electrical components. *A node* is a point of the circuit where several branches end. *A mesh* comprises of two or more branches that together form a closed loop.

The description of the equations corresponding to the electrical circuit is based on Kirchoffôs laws:

- the nodes law or 1st Kirchoffôs law states that: *the sum of the currents flowing into a node must equal the sum of the currents flowing out of the node;*
- the mesh law or 2nd law of Kirchoff states that: *for any circuit mesh, the algebraic sum of the voltages at the terminals of branches that form the mesh is null.*

Kinematic coupling is also part of the physical proprieties description. The kinematic module enables the study of the displacement of a moving part of a device determined by mechanical forces (due to springs, friction, gravity, etc.), and electromagnetic forces (generated by magnets, coils, etc.). We deal in this case with the magneto-mechanical coupling (or studies with kinematic coupling). It can be used for the numerical modeling of devices, such as motors, electro-valves, switches and so on.

Three different kinematic models are available: ñ*multi static*ò model, ñ*imposed speed*ò model, ñ*coupled load*ò model.

Multi static kinematic model:

In the multi static kinematic model, the moving part of the device is not moving. The computation of the electromagnetic field is carried out for various arbitrary relative positions of moving and fixed parts. This model performs a set of Magneto Static computations (Ö/Öt = 0 in Maxwellôs equations), and does not take into consideration the dynamics equation.

This model is equivalent to a parameterized study where the position of the moving part is a varying parameter. This model can also be used with the Transient Magnetic and Steady state AC Magnetic applications.

Imposed speed kinematic model:

In the imposed speed kinematic model, the moving part is considered as moving at a constant velocity with respect to the fixed part. The computation of the electromagnetic field is carried out for the different positions defined by the imposed speed of the moving part. As in the previous kinematic model (multi static), the dynamics equation is not considered.

In the imposed speed kinematic model, the physical application used is the Transient Magnetic physical application. In this case, the Maxwellôs equations consider the time dependence of the electromagnetic field (Ö/Öt Í 0).

Coupled load kinematic model:

In the coupled load kinematic model, the moving part drives an external device that represents the mechanical load of the studied device. This is the model where the magneto-mechanical coupling is considered, that is to say, both the magnetic aspect and the kinematic aspect of a problem. The physical application used is the Transient Magnetic application.

- ***Solving and results post-processing***

The solving processor, based on the second order finite element method, supplies the value of a variable (potential, temperature, etc.) at each node of the mesh. In transient problems, a solution is obtained for each time step.

The main tasks carried out by the solving process are:

- *the integration and the assembling*, which are carried out simultaneously. The elements are analyzed one by one, the integrals are computed, the sub-matrix and the right hand side member related to each element are built, and the elementary sub-matrixes are assembled in order to build the general matrix of the set of linear equations to be solved. It is during this assembling process that the boundary conditions are taken into account.
- *the solving of the set of linear equations by ICCG (Incomplete Choleski Conjugated Gradients) method.*
- if the set of equations is not linear (physical properties varying non-linearly), these computations are repeated on the non-linear elements, according to an *iterative process (Newton-Raphson).*

Results of a computation can be analyzed in several different ways. These results can be displayed on the screen, saved to a file, printed on paper, copied into the clipboard. When using symmetries, you can reconstruct the full device for the visualization of different views. Several options allow you to customize the analysis of the results.

The program allows the analysis of the results on previously created supports. A support allows the user to perform a computation over a zone different from a point.

Three types of supports are currently available: *the path*, *the group of regions or electrical components* and *the grid of points*.

The user has the possibility to create as many supports as he wishes and to record them for a later analysis by simply saving the file. During the result analysis, the supports created are added to the tree.

All the local quantities, including the field sources and the material characteristics, can be displayed in the form of *isovalue lines* or *color-shaded plots* on a region, on a group of regions or on all the regions.

All the vector quantities (flux density, magnetic field, etc.) can be represented in the form of *vectors* on a region (or on a group of regions or on all the regions), on a region boundary (boundary vectors), or along a path.

Different computations in the form of 2D curves can also be performed.

There are five types of 2D curves:

- curves along a path or along a shell region (computation of local quantities),
- time-dependent or parameter-dependent curves,
- spectra : FFT computation, available for any curve already created,
- characteristic curves of the regions,
- imported curves.

The 2D curves can be done in three steps:

- first, it has to be created the curve by using a 2D curve manager,
- then, it has to be displayed on the screen (2D sheet),
- finally, the user can analyze the results with tools related to 2D curves.

Some computations can be performed in order to display the results as 3D curves.

There are five types of 3D curves:

- curves along a path and function of a parametric variation
- curves along a shell region and function of a parametric variation,
- curves associated to the computation on a geometric grid,
- curves function of the variation of two parameters,
- imported curves

The same three steps should be carried out when post-processing a problem by means of 3D curves, as in 2D curves.

Different particular quantities such as: inductance, force and torque, iron losses, losses in a dielectric material, etc. are also computed; a list of the displayable quantities for each application being presented in Table 4.

Table 4: List of the displayable quantities for each application

	Color shaded plots	Isovalue lines vectors	Boundary vectors
Axipériodic	scalar potential magnetic field flux density permeability B-theta B-rtz	magnetic field flux density	magnetic field flux density
Dielectrics Dielectro-thermal* (Dielectric part)	|electric field| |current density| power density |flux density| permittivity potential resistivity temperature*	electric field electric flux density	electric field electric flux density
Electrokinetics Electro-thermal* (Electric-part)	|electric field| |current density| power density potential resistivity temperature*	electric field current density	electric field current density
Electrodynamics	magnetic field |current density| power density permeability resistivity	current density	current density
Electrostatics	|electric field| charge density power density |electric flux density| permittivity potential tangent delta	electric field electric flux density	electric field electric flux density
Magnetostatics Magnetodynamics Transient magnetics Magneto-thermal* (magnetic part)	|magnetic field| current density power density flux |flux density| permeability vector potential resistivity temperature*	magnetic field flux density	magnetic field magnetic pressure flux density
Thermal	conductivity power density temperature	-	-
Transient thermal	specific heat conductivity power density temperature	-	-

II.4.3. MATLAB Simulink - Simulation and Model Based Design

- ***What is MATLAB Simulink?***

MATLAB is a high-level language and interactive environment for numerical computation, visualization, and programming. Using MATLAB, one can analyze data, develop algorithms, and create models and applications. The language, tools, and built-in math functions enable users to explore multiple approaches and reach a solution faster than with spreadsheets or traditional programming languages, such as C/C++ or Java.

MATLAB can be used for a large range of applications, including signal processing and communications, image and video processing, control systems, test and measurement, computational finance, and computational biology. More than a million engineers and scientists in industry and academia use MATLAB, the language of technical computing.

Simulink is a block diagram environment for multi-domain simulation and Model-Based Design. It supports system-level design, simulation, automatic code generation, and continuous test and verification of embedded systems.

Simulink provides a graphical editor, customizable block libraries, and solvers for modeling and simulating dynamic systems. It is integrated with MATLAB, enabling you to incorporate MATLAB algorithms into models and export simulation results to MATLAB for further analysis.

Simulink offers:

- a quick way of developing models in contrast to text based-programming language
- it has integrated solvers. In text based-programming language the user need to write its own solver.

In the last years the ability to use tools such as MATLAB Simulink has become a requirement for many engineering positions, not only in electrical engineering, but biomedical engineering and fluid dynamics as well.

- ***Simulation and Model Based Design***

Model-Based Design is a process that enables faster, more cost-effective development of dynamic systems, including control systems, signal processing, and communications systems. In Model-Based Design, a system model is at the center of the development process, from requirements development, through design, implementation, and testing. The model is an executable specification that can be continually refined throughout the development process. After model development, simulation shows whether the model works correctly.

When software and hardware implementation requirements are included, such as fixed-point and timing behavior, the code for embedded deployment and create test benches for system verification, can be automatically generated, saving time and avoiding the introduction of manually coded errors.

Model-Based Design improves efficiency by:

- Using a common design environment across project teams
- Linking designs directly to requirements
- Integrating testing with design to continuously identify and correct errors
- Refining algorithms through multi-domain simulation
- Automatically generating embedded software code
- Developing and reusing test suites
- Automatically generating documentation
- Reusing designs to deploy systems across multiple processors and hardware targets

- ***Model-Based Design Process***

There are six steps to modeling any system:

- Defining the System
- Identifying System Components
- Modeling the System with Equations
- Building the Simulink Block Diagram
- Running the Simulation
- Validating the Simulation Results

The first three steps of this process are performed outside of the Simulink software environment before you begin building your model.

Defining the System

The first step in modeling a dynamic system is to fully define the system. If a large system that can be broken into parts is modeled, then each subcomponent should be modeled on its own. Then, after building each component, it can be integrated into a complete model of the system. The most effective way to build a model of a system is to consider each of the subsystems independently.

Identifying System Components

The second step in the modeling process is to identify the system components. Three types of components define a system:

- *Parameters* ð System values that remain constant unless you change them
- *States* ð Variables in the system that change over time
- *Signals* ð Input and output values that change dynamically during a simulation

In Simulink, parameters and states are represented by blocks, while signals are represented by the lines that connect blocks. For each subsystem that you identified, ask yourself the following questions:

- How many input signals does the subsystem have?
- How many output signals does the subsystem have?
- How many states (variables) does the subsystem have?
- What are the parameters (constants) in the subsystem?
- Are there any intermediate (internal) signals in the subsystem?

Once these questions were answered, a comprehensive list of system components should be generated, and the modeling process of the system can be stareted.

Modeling the System with Equations

The third step in modeling a system is to formulate the mathematical equations that describe the system. For each subsystem, use the list of system components that were identified to describe the system mathematically.

The model may include:

- Algebraic equations
- Logical equations
- Differential equations, for continuous systems
- Difference equations, for discrete systems

These equations will be used to create the block diagram in Simulink.

Building the Simulink Block Diagram

After the mathematical equations that describe each subsystem were defined, building a block diagram of the model in Simulink can began.

The block diagram for each subcomponent can be built separately. After each subcomponent has been modeled, it can be integrated into a complete model of the system.

Running the Simulation

After the Simulink block diagram were build, the model can be simulated and the results analyzed. Simulink allows interactively defining system inputs, simulating the model, and observing changes in behavior. This ensures a quickly evaluation of the model.

Validating the Simulation Results

Finally, it must be checked if the model accurately represents the physical characteristics of the dynamic system.

The linearization and trimming tools available from the MATLAB command line can be used, plus the many tools in MATLAB and its application toolboxes to analyze and validate the developed model.

II.4.4. Motor-CAD

Motor-CAD is a unique software package dedicated to the electromagnetic performance of motors and generators and the optimization of their cooling. Developed more than 12 years ago, Motor-CAD is used by major motor manufacturers and universities worldwide.

Motor-CAD provides the ability to quickly and easily perform electromagnetic and thermal performance tests on prototype designs. Accurate electromagnetic and thermal calculations can be done in seconds. The results are presented in an easy to understand form for analysis to allow design decisions to be taken in an efficient manner.

The software has a carefully constructed user interface that makes for easy data input and interpretation of results. Many of the features, that make Motor-CAD the perfect optimization tool, have been developed in close consultation with customers to meet the needs of the industry. This image shows the 3D view of the motor from within Motor-CAD.

Four Motor-CAD modules are developed:

- Motor-CAD EMag
- Motor-CAD Thermal
- Motor-CAD FE-Therm

Motor-CAD EMag:

The new Motor-CAD BPM-EMag module works with the existing Motor-CAD thermal design modules for brushless permanent magnet machines (BPM), with inner and outer rotor configurations, enabling motor designers to produce optimum designs for performance, energy efficiency, size and cost reduction. Motor-CAD makes the best use of the latest modeling techniques to provide the fast and accurate analysis tool for machine designers. The standard industrial tests for BPM machines are modeled as electromagnetic performance tests that take into account the thermal aspects of the machine.

Motor-CAD Thermal

The thermal model in Motor-CAD is based upon analytical lumped-circuit analysis making it extremely fast to calculate. This allows the user to perform 'what-if' calculations in real time. Alternative numerical methods typically require days or even weeks to model and several hours to calculate a solution.

All the thermal resistances and capacitances in the Motor-CAD model are calculated automatically from geometric dimensions and material properties. The user does not need to be familiar with complex heat transfer phenomena such as dimensionless analysis correlations for convection. Motor-CAD automatically selects and solves the most appropriate formulation for a given surface and the cooling type selected. Motor-CAD features efficient, accurate and robust mathematical algorithms for forced and natural convection, liquid cooling, radiation and conduction. An extensive library of proven laminar and turbulent convection correlations are used to give accurate models for all internal and external surfaces. The airgap model includes laminar, vortex and turbulent convection.

The software is used to optimize the cooling of a wide variety of motor types and cooling methods. The fast calculation speeds are huge benefit when modeling complex duty cycles, such as traction motor drive cycles, and applications such as elevator load cycles.

Motor-CAD modules are available for the following motor types:

- brushless permanent magnet motors (BPM)
- outer rotor BPM motors induction motors
- permanent magnet DC machines

- switched reluctance motors
- synchronous machines
- claw pole machines
- universal motors

There are many different motor types, housing types and cooling types available in Motor-CAD.

Motor-CAD models are available for the following cooling methods:

- natural convection (TENV)
- forced convection (TEFC)
- through ventilation
- water jackets (several configurations)
- submersible
- flooded
- wet rotor and wet stator
- spray cooling
- radiation
- conduction

Users are also able to include various mounting configurations in the model that can provide heating or extra cooling to the machine.

FE-Therm Module

MDL's FE-Therm add-on module provides increased detail on conduction heat transfer in various components. It can be used to analyze conduction heat transfer for complex geometries such as multi-layer interior magnet motor rotors.

FE-Therm can be used to calibrate analytical lumped circuit models, thus improving accuracy. It is fully automated and takes only a few seconds to calculate.

Motor-CAD software is used in various and complex applications, such as hybrid/electric vehicles, green aircrafts, wind power generation, submersible pumps, hermetic compressors, conveyer rollers and racing cars.

Chapter III: *Materials Selection*

This chapter provides a comprehensive treatment of the selection of materials for manufacturing the design. Materials and the manufacturing processes that convert them into useful parts underlie all of engineering design. There are over 100000 engineering materials to choose from. The typical design engineer should have ready access to information on 30 to 60 materials, depending on the range of application.

The recognition of the importance of materials selection in design has increased in recent years. Concurrent engineering practices have brought materials specialists into the design process at an earlier stage. The importance given to quality and cost aspects of manufacturing in present-day product design has emphasized the fact that materials and manufacturing are closely linked in determining final product performance. Moreover, the pressures of worldwide competition have increased the level of automation in manufacturing to the point where material costs comprise 60% or more of the cost for most products. Finally, the extensive activity in materials science worldwide has created a variety of new materials and focused our attention on the competition between six broad classes of materials: metals, polymers, elastomers, ceramics, glasses, and composites. Thus, the range of materials available to the engineer is much broader than ever before. This presents the opportunity for innovation in design by utilizing these materials to provide greater performance at lower cost. Achieving these benefits requires a rational process for materials selection.

III.1. Materials Selection in Design Process

An incorrectly chosen material can lead not only to failure of the part but also to excessive life-cycle cost. Selecting the best material for a part involves more than choosing both a material that has the properties to provide the necessary performance in service and the processing methods used to create the finished part.

A poorly chosen material can add supplementary manufacturing cost. Properties of the material can be enhanced or diminished by processing, and that may affect the service performance of the part or the final product.

Faced with the large number of combinations of materials and processes from which to choose, the materials selection task can only be done effectively by applying simplification and systemization. As design proceeds from concept design, to configuration and parametric design (embodiment design), and to detail design, the material and process selection becomes more detailed.

Fig. 29 compares the design methods and tools used at each design stage with materials and processes selection. At the concept level of design, essentially all materials and processes are considered in broad detail. The task is to determine whether each design concept will be made from metal, plastics, ceramic, composite, or wood, and to narrow it to a group of materials within that material family. The required precision of property data is rather low.

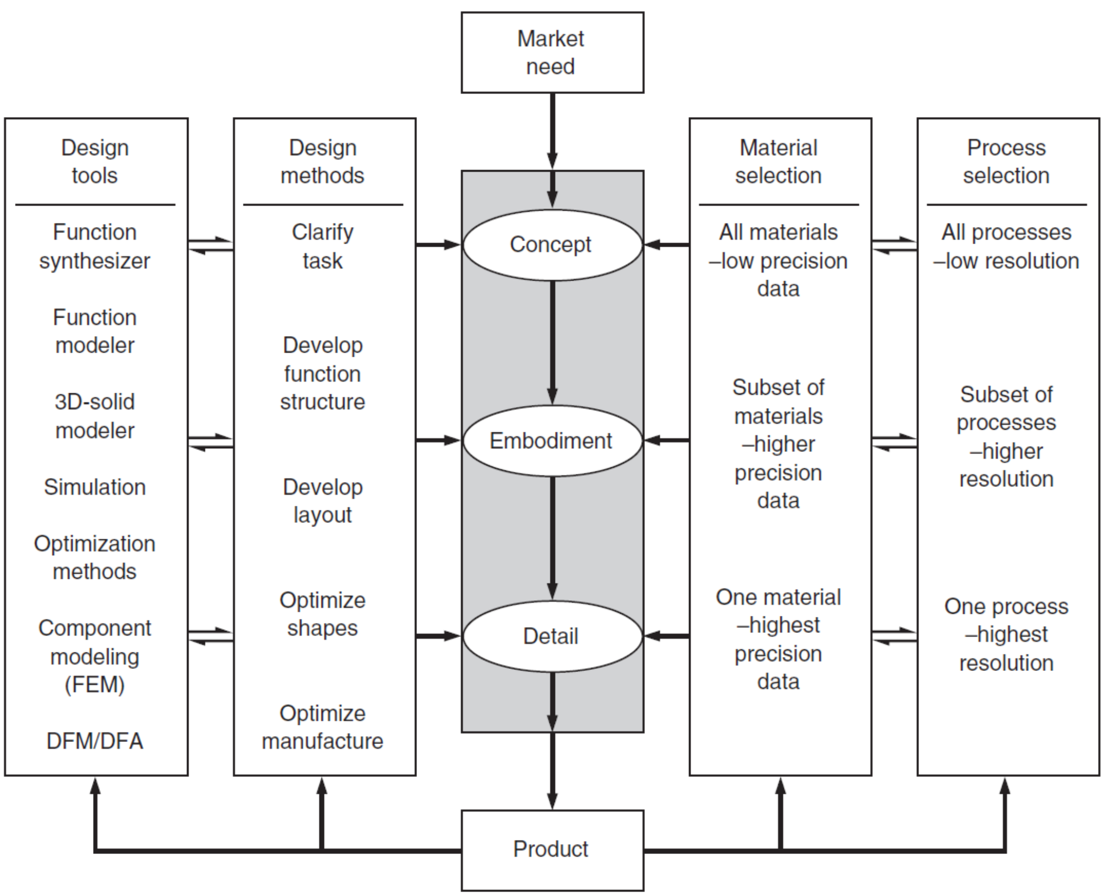


Fig. 29: Schematic of the design process

Note that if an innovative choice of material is to be made it must be done at the conceptual design phase because later in the design process too many decisions have been made to allow for a radical change. The emphasis at the embodiment phase of design is on determining the shape and size of a part using engineering analysis. The designer will have decided on a class of materials and processes, such as a range of aluminum alloys, wrought and cast. The material properties must be known to a greater level of precision. At the parametric design step the alternatives will have narrowed to a single material and only a few manufacturing processes. Here the emphasis will be on deciding on critical tolerances, optimizing for robust design, and selecting the best manufacturing process using quality engineering and cost modeling methodologies. Depending on the importance of the part, materials properties may need to be known to a high level of precision. This may require the development of a detailed database based on an extensive materials testing program. Thus, material and process selection is a progressive process of narrowing from a large universe of possibilities to a specific material and process.

There are two approaches to settling on the material-process combination for a part:

- *material-first approach*
- *process-first approach*

In the *material-first approach*, the designer begins by selecting a material class and narrowing it down as described previously. Then manufacturing processes consistent with the selected material are considered and evaluated. Chief among the factors to consider are production volume and information about the size, shape, and complexity of the part.

With the *process-first approach*, the designer begins by selecting the manufacturing process, guided by the same factors. Then materials consistent with the selected process are considered and evaluated, guided by the performance requirements of the part. Both approaches end up at the same decision point.

Most design engineers and materials engineers instinctively use the materials-first approach, since it is the method taught in strength of materials and machine design courses. Manufacturing engineers and those heavily involved with process engineering gravitate toward the other approach.

- ***Materials Selection in Conceptual Design***

While materials selection issues arise at every phase in the design process, the opportunity for greatest innovation in materials selection occurs at the conceptual design phase. At this phase all options are open. The designer requires approximate data on the broadest possible range of materials.

In the conceptual design phase the objective is to select a material class for the critical components and a suggested set of possible manufacturing processes. Different design concepts could lead to the selection of different material classes for their implementation. A cast aluminum alloy may be the best material for one design concept, while a polymer is best for a different concept, even though the two concepts provide the same function.

- ***Materials Selection in Embodiment Design***

A more comprehensive materials selection process is typically carried out in the embodiment design phase. At the beginning there are parallel materials selection and component design paths to follow. The input to the material selection process is a small set of tentative materials chosen in conceptual design. At the same time in the configuration design step of embodiment design, a tentative component design is developed that satisfies the functional requirements, and, using the material properties, an approximate stress analysis is carried out to calculate stresses and stress concentrations. The two paths merge in an examination of whether the best material, fabricated into the component by its expected manufacturing process, can bear the loads, moments, and torques that the component is expected to withstand.

Often the information is inadequate to make this decision with confidence and finite element modeling or some other computer-aided predictive tool is used to gain the needed knowledge. Alternatively, a prototype component is made and subjected to testing. Sometimes it becomes clear that the initial selections of materials are just inadequate, and the process iterates back to the top and the selection process starts over.

When the material-process selection is deemed adequate for the design, the choice passes to a detailed specification of the material and the design. This is the parametric design step. In this design step, an attempt should be made to optimize the critical dimensions and tolerances to achieve a component that is robust to its service environment, using an approach such as the Taguchi methodology. The next step is to finalize the choice of the production method. This is based on a detailed calculation of the cost to manufacture the component. The material cost and the inherent workability and formability of the material, to reduce scrapped parts, are a major part of this determination.

Another important consideration is the quality of the manufactured component, again strongly influenced by the choice of material. Still other considerations are the heat treatment, surface finishing, and joining operations that will be required.

Once the component goes into production, the early runs will be used to fine-tune the manufacturing process and to gage the market receptivity to the product. If this is satisfactory, then full-scale production is established. However, it is important to follow the service experience of the product to determine any weak or potential points of failure, to identify parts of the design that could be improved by a redesign, or to determine ways to reduce cost using value analysis.

III.2. General Criteria for Selection

Materials are selected on the basis of four general criteria:

- *Performance characteristics (properties)*
- *Processing (manufacturing) characteristics*
- *Environmental profile*
- *Business considerations*

Selection on the basis of performance characteristics is the process of matching values of the properties of the material with the requirements and constraints imposed by the design.

Selection on the basis of processing characteristics means finding the process that will form the material into the required shape with a minimum of defects at the least cost.

Selection on the basis of an environmental profile is focused on predicting the impact of the material throughout its life cycle on the environment. In the last years environmental considerations are growing in importance because of the dual pressures of greater consumer awareness and governmental regulation.

The business consideration that affects materials selection is the cost of the part that is made from the material. This considers both the purchase cost of the material and the cost to process it into a part. A more exact basis for selection is life-cycle cost, which includes the cost of replacing failed parts and the cost of disposing of the material at the end of its useful life.

III.2.1. Performance Characteristics of Materials

The performance or functional requirements of a material usually are expressed in terms of physical, mechanical, thermal, electrical, or chemical properties. Material properties are the link between the basic structure and composition of the material and the service performance of the part.

Materials science predicts how to improve the properties of materials by understanding how to control their structure. Structure can vary from atomic dimensions to the dimensions of a few millimeters. The main methods of altering structure are through composition control (alloying), heat treatment, and controlling the processing of the material. A general background in the way structure determines the properties of solid materials usually is obtained from a course in materials science or fundamentals of engineering materials.

Since structure determines properties, everything about materials is structure. The term structure has different meanings as we change the scale of observation. To materials scientists, structure describes the way atoms and larger configurations of atoms arrange themselves, but to the design engineer structure refers to the form of a component and how the forces are applied to it. At the atomic level, materials scientists are concerned with basic forces between atoms, which determine the density, inherent strength, and Youngôs modulus. Moving upward in scale, they deal with the way the atoms arrange themselves in space, that is, the crystal structure. Crystal type and lattice structure determine the slip plane geometry and ease of plastic deformation. Superimposed on the crystal structure is the defect structure or the imperfections in the perfect three-dimensional atomic pattern. The defect structure greatly influences the properties of materials. At a higher scale of observation, such as that seen through an optical microscope, we observe the microstructure features such as grain size and the number and distribution of individual crystal phases. Finally, with a low-power microscope, we may observe porosity, cracks, seams, inclusions, and other gross features of the macrostructure.

- ***Classification of Materials***

Materials can be divided into metals, ceramics, and polymers. Further division leads to the categories of elastomers, glasses, and composites. Finally, there are the technologically important classes of optical, magnetic, and semiconductor materials.

An *engineering material* is a material that is used to fulfill some technical functional requirement, as opposed to being just used for decoration. Those materials that are typically used to resist forces or deformations in engineering structures are called *structural materials*.

Engineering materials usually are not made up of a single element or one type of molecule. Many elements are added together in a metal to form an alloy with specially tailored properties. For example, pure iron (Fe) is rarely used in the elemental state, but when it is alloyed with small amounts of carbon to form steel its strength is improved markedly. This is brought about by the formation throughout the solid of strong intermetallic compound Fe_3C particles. The degree of strengthening increases with the amount of iron carbide, which increases with the carbon content. However, an overriding influence is the distribution and size of the carbide particles in the iron matrix. The distribution is controlled by such processing operations as the hot rolling or forging of the steel, or by its thermal treatment such as quenching or annealing. Thus, there are a great variety of properties that can be obtained in a given class of alloys. The same applies to polymers, where the mechanical properties depend upon the types of chemical groups that make up the polymer chain, how they are arranged along the chain, and the average length of the chain (molecular weight).

Thus, there is a material classification hierarchy, starting with the *Materials Kingdom* (all materials) Ÿ *Family* (metals, polymers, etc.) Ÿ *Class* (for metals: steels, aluminum alloys, copper alloys, etc.) Ÿ *Subclass* (for steels: plain carbon, low-alloy, heat treatable, etc.) Ÿ *Member* (a particular alloy or polymer grade). A member of a particular family, class, and subclass of materials has a particular set of attributes that we call its material properties. The classification does not stop here, because for most materials the mechanical properties depend upon the mechanical (plastic deformation) or thermal treatment it has last been given.

- ***Properties of Materials***

The performance or functional requirements of a material are usually given by a definable and measurable set of material properties. The first task in materials selection is to determine which material properties are relevant to the application. We look for material properties that are easy and inexpensive to measure, are reproducible, and are associated with a material behavior that is well defined and related to the way the material performs in service.

A property may be a constant or may be a function of one or more independent variables, such as temperature. Materials properties often vary to some degree according to the direction in the material in which they are measured, a condition referred to as anisotropy. Materials properties that relate two different physical phenomena often behave linearly (or approximately so) in a given operating range, and may then be modeled as a constant for that range. This linearization can significantly simplify the differential constitutive equations that the property describes.

Some materials properties are used in relevant equations to predict the attributes of a system a priori. For example, if a material of a known specific heat gains or loses a known amount of heat, the temperature change of that material can be determined. Materials properties are most reliably measured by standardized test methods. Many such test methods have been documented by their respective user communities and published through *ASTM International*.

Materials properties can be classified into:

- *Chemical properties*: corrosion resistance, hygroscopy, pH, reactivity, specific internal surface area, surface energy, surface tension;
- *Electrical properties*: dielectric constant, dielectric strength, electrical conductivity, permittivity, piezoelectric constants, seebeck coefficient;
- *Magnetic properties:* Curie temperature, diamagnetism, hysteresis, permeability
- *Mechanical properties:* compressive strength, creep, ductility, fatigue limit, flexural modulus, flexural strength, fracture toughness, hardness, plasticity, Poisson's ratio, resilience, shear modulus, shear strain, shear strength,

specific modulus, specific strength, specific weight, tensile strength, yield strength, coefficient of friction, coefficient of restitution, surface roughness;

- *Optical properties*: absorptivity, birefringence, color, luminosity, photosensitivity, reflectivity, refractive index, scattering, transmittance;
- *Thermal properties*: autoignition temperature, binary phase diagram, boiling point, coefficient of thermal expansion, critical temperature, Curie point, emissivity, eutectic point, flammability, flash point, Glass transition temperature, heat of fusion, heat of vaporization, inversion temperature, melting point, phase diagram, pyrophoricity, solidus, specific heat, thermal conductivity, thermal diffusivity, thermal expansion, seebeck coefficient, triple point, vapor pressure.

III.2.2. Processing (manufacturing) characteristics

There is a close interdependence between material selection and process selection. Just as shape requirements limit the available selection of processes, the selection of a material also places certain restrictions on the available manufacturing processes. The melting point of the material and its level of deformation resistance and ductility are main factors. The melting point of the material determines the casting processes that can be employed. Low-melting-point metals can be used with a wide number of casting processes, but as the melting point rises, problems with mold reaction and atmosphere contamination limit the available processes. Some materials, like ceramics, may be too brittle for shape creation by deformation processes, while others are too reactive to have good weldability.

The factors that influence the selection of a process to make a part are:

- *Quantity of parts required*
- *Complexity*ð shape, size, features
- *Material*
- *Quality of part*
- *Cost to manufacture*
- *Availability*

The steps in selecting a manufacturing process are:

- Based on the part specification, identify the material class, the required number of parts, and the size, shape, minimum thickness, surface finish, and tolerance on critical dimensions of the part. These constitute constraints on the selection of the process.

- Decide what the objective of the process selection process is. Generally, the objective is to minimize the cost of the manufactured part. However, it might be to maximize the quality of the part, or to minimize the time to make it.
- Using the identified constraints, screen a large number of processes to eliminate the processes incapable of meeting them.
- Having narrowed the possible processes to a smaller number, they should be ranked based on manufacturing cost. A quick ranking can be based on the economic batch size, but a cost model is needed for the final decision.

III.2.3. Environmental profile

The heightened public awareness of environmental issues has resulted in significant legislation and regulation that provide new constraints on design. Traditionally the recycling and reuse of materials was dictated completely by economics.

Those materials like steel, copper, and more recently aluminum, which can be collected and reprocessed at a profit, were recycled. However, with widespread popular support for improving the environment, other benefits of recycling are being recognized.

The complete life cycle of a material is shown in Fig. 30. The materials cycle starts with the mining of a mineral or the drilling for oil or the harvesting of an agricultural fiber like cotton. These raw materials must be processed to refine or extract bulk material that is further processed into a finished engineering material. At this stage an engineer designs a product that is manufactured from the material, and the product is put into useful service. Eventually the product wears out or is made obsolete because a better product comes on the market. At this stage our tendency has been to junk the product and dispose of it in some way, like a landfill, that eventually returns the material to the earth.

However, society is more and more mindful of the dangers to the environment of such haphazard practices. As a result, more emphasis is being placed on recycling of the material directly back into the materials cycle.

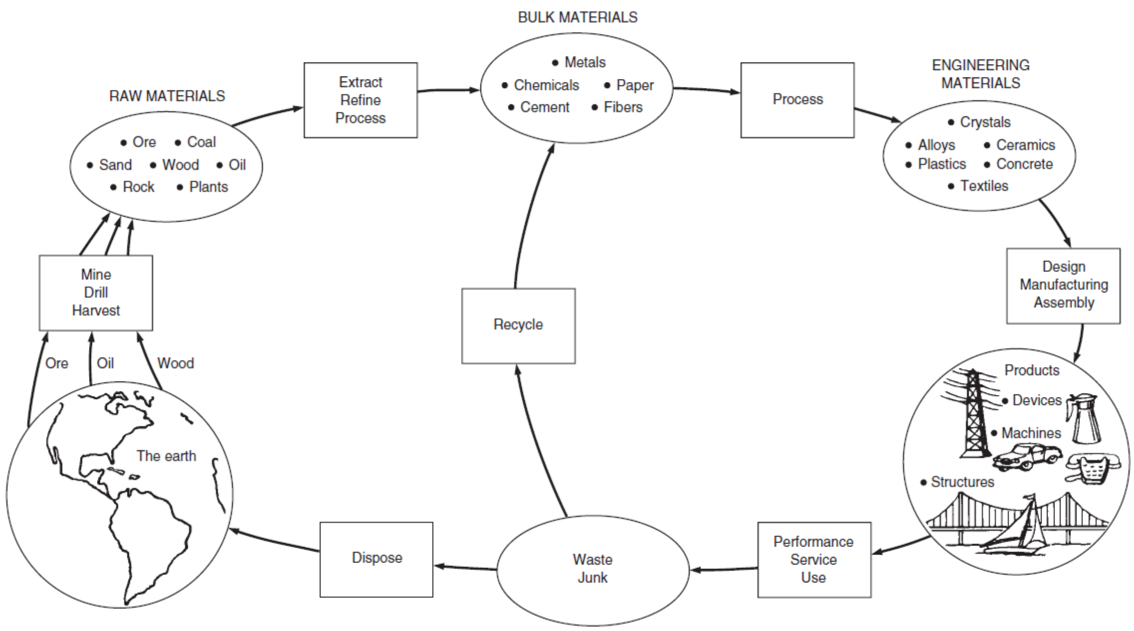


Fig. 30: Total materials cycle

- ***Benefits of Recycling***

The obvious benefits of materials recycling are the contribution to the supply of materials, with corresponding reduction in the consumption of natural resources, and the reduction in the volume of solid waste. Moreover, recycling contributes to environmental improvement through the amount of energy saved by producing the material from recycled (secondary) material rather than primary sources.

Recycling of materials also directly reduces pollution. For example, the use of steel scrap in making steel bypasses the blast furnace at a considerable economic benefit. Bypassing the blast furnace in processing eliminates the pollution associated with it, particularly since there is no longer a need for the production of coke, which is an essential ingredient for blast furnace smelting.

An alternative to recycling is remanufacturing. Instead of the product being disassembled for recycling, remanufacturing restores it to near new condition by cleaning and replacement of worn parts. We have long been familiar with rebuilt automotive parts, like alternators and carburetors, but now remanufacture has moved to appliances such as copiers and printers, and to large engineered products like diesel engines and construction equipment.

- ***Design for Recycling***

There are several steps that the designer can take to enhance the recyclability of a product:

- Make it easier to disassemble the product, and thus enhance the yield of the separation step.
- Minimize the number of different materials in the product to simplify the identification and sorting issue.
- Choose materials that are compatible and do not require separation before recycling.
- Identify the material that the part is made from right on the part.

These guidelines can lead to contradictions that require serious trade-offs. Minimizing the number of materials in the original product may require a compromise in performance from the use of a material with less-than-optimum properties. In the past, decisions of this type would be made exclusively on the basis of cost. Today, we are moving toward a situation where the customer may be willing to pay extra for a recyclable design, or the recyclable design may be mandated by government regulations. Decision making on recycling requires input from top management in consultation with material recycling experts.

III.2.4. Business considerations

Ultimately the material-process decision on a particular design will come down to a trade-off between performance and cost. There is a continuous spectrum of applications, varying from those where performance is paramount (aerospace and defense are good examples) to those where cost clearly predominates (household appliances and low-end consumer electronics). In the latter type of application the manufacturer does not have to provide the highest level of performance that is technically feasible. Rather, the manufacturer must provide a value-to-cost ratio that is no worse, and preferably better, than the competition. By value we mean the extent to which the performance criteria appropriate to the application are satisfied.

An engineering design is not complete until we have a good idea of the cost required to build the design or manufacture the product. Generally, among functionally equivalent alternatives, the lowest-cost design will be successful in a free marketplace.

Understanding the elements that make up cost is vital because competition between companies and between nations is fiercer than ever. The world is becoming a single gigantic marketplace in which newly developing countries with very low labor costs are acquiring technology and competing successfully with the well-established industrialized nations. Maintaining markets requires a detailed knowledge of costs and an understanding of how new technology can lower costs.

Decisions made in the design process commit 70 to 80% of the cost of a product. It is in the conceptual and embodiment design stages that a majority of the costs are locked into the product.

Cost estimates are used in the following ways:

- To provide information to establish the selling price of a product or a quotation for a good or service.
- To determine the most economical method, process, or material for manufacturing a product.
- To become a basis for a cost-reduction program.
- To determine standards of production performance that may be used to control costs.
- To provide input concerning the profitability of a new product.

- ***Design to cost***

Design to cost, also called target costing, is the approach in which a target value, (sometimes called ñshould-costò data), for the cost of a product is established at the beginning of a product development project. All design decisions are examined for their impact on keeping below the target cost. This is in contrast with the more usual practice of waiting for a complete cost analysis in the detail design phase. If this proves to be excessive, then the only practical recourse is to try to wring the excess cost out of the manufacturing process or to substitute a less expensive material, often at the expense of quality.

The steps in accomplishing design to cost are:

- *Establish a realistic and reliable target cost*. The target cost is the difference between a realistic estimate of what the customer will pay for the product when developed minus the expected profit. This requires effective and realistic market analysis and an agile product development process that gets the product to market in minimum time.

- *Divide the target cost into subunits*. The basis for dividing the total cost can be cost of subsystems and components in similar designs, division according to competitorsô component costs, or on the basis of estimates of what the customer is willing to pay for various functions and features of the product.

- *Oversight of compliance with cost targets.* A major difference in the design to cost approach is that the cost projections will be evaluated after each design phase and before going into production. For this to be effective there must be cost evaluation methods that can be applied at an earlier stage than detail design. There must also be a systematic way of quickly making cost comparisons.

- ***Cost of Materials***

Cost is such an overpowering consideration in many materials selection situations that we need to give this factor additional attention. The basic cost of a material depends upon scarcity, as determined by:

- the concentration of the metal in the ore,
- the cost of the feedstock for making a polymer,
- the cost and amount of energy required to process the material,
- the basic supply and demand for the material.

In general, large-volume-usage materials like stone and cement have very low prices, while rare materials, like industrial diamonds, have very high prices. As more work is invested in the processing of a material, the cost increases. Improvement in properties, like yield strength, beyond those of the basic material are produced by changes in structure brought about by compositional changes and additional processing steps. For example, increases in the strength of steel are achieved by expensive alloy additions such as nickel, by heat treatment such as quenching and tempering, or by vacuum treatment of the liquid steel to remove gaseous impurities. However, the cost of an alloy may not simply be the weighted average of the cost of the constituent elements that make up the alloy. Often, a high percentage of the cost of an alloy is due to the need to control one or more impurities to very low levels. That could mean extra refining steps or the use of expensive high-purity raw materials (electrical copper).

Because most engineering materials are produced from nonrenewable resources, mineral ores or oil and natural gas, there is a continuous upward trend of cost over time. As commodities, materials fluctuate in price due to temporary over/or undersupply.

Over the long term the cost of materials has risen at a rate about 10% greater than the costs of goods and services in general. Therefore, conservation in the use of materials is increasingly important.

To compensate for the change in the prices of materials over time, costs are often normalized relative to a common inexpensive material such as a steel reinforcing bar or a plain carbon steel plate.

The cost structure for pricing many engineering materials is quite complex, and true prices can be obtained only through quotations from vendors. Reference sources typically give only the nominal or baseline price. The actual price depends upon a variety of price extras in addition to the base price (very much as when a new car is purchased). The actual situation varies from material to material.

Chapter IV: *Parts Manufacturing*

Manufacturing, in its broadest form, refers to óóthe design, fabrication (production), and, when needed, assembly of a productôô.

In its narrower form, however, the term has been frequently used to refer to the actual physical creation of the product. In this latter context, the manufacturing of a product based on its design specifications is carried out in a discrete-parts mode or a continuous-production mode.

This chapter is focused on the discrete parts manufacturing. Continuous-production processes used in some metal, chemical, petroleum, and pharmaceutical industries will not be addressed herein.

IV.1. Metal Casting

Casting is a term normally reserved for the net shape formation of a metal object by pouring (or forcing) molten (metal) material into a mold (or a die) and allowing it to solidify. The molten metal takes the shape of the cavity as it solidifies.

Cast objects may be worked on further through other metal-forming or machining processes in order to obtain more intricate shapes, better mechanical properties, as well as higher tolerances.

The most common casting material is iron. The widely used generic term cast iron refers to the family of alloys comprising different proportions of alloying material for iron-carbon and silicon, primarily, as well as manganese, sulphur, and phosphorus.

Gray cast iron:

The chemical composition of gray cast iron contains 2.5ï 4% carbon, 1ï 3% silicon, and 0.4ï 1% manganese. Due to its casting characteristics and cost, it is the most commonly used material (by weight). Its fluidity makes it a desirable material for the casting of thin and intricate features. Gray cast iron also has a lower shrinkage rate, and it is easier to machine. A typical application is its use in the manufacture of engine body.

Gray cast iron can be further alloyed with chromium, molybdenum, nickel, copper, or even titanium for increased mechanical properties: strength, resistance to wear, corrosion, abrasion, etc.

Ductile cast iron:

The chemical composition of ductile cast iron (also known as nodular or spheriodal graphite cast iron) contains 3ï 4% carbon, 1.8ï 2.8% silicon, and 0.15ï 0.9% manganese. First introduced in the late 40ôs, this material can also be cast into thin sections (though not as well as gray cast iron). It is superior in machinability to gray cast iron at equivalent hardness. Its corrosion and wear resistance is superior to steel and equivalent to gray cast iron. Typical uses of ductile cast iron include gears, crankshafts, and cams.

Malleable iron:

The chemical composition of malleable iron contains 2ï 3.3% carbon, 0.6ï 1.2% silicon, and 0.25ï 0.65% manganese. It can normally be obtained by heat-treating white iron castings. The high strength of malleable iron combined with its ductility makes it suitable for applications such as camshaft brackets, differential carriers, and numerous housings.

One must note that malleable iron must be hardened in order to increase its relatively low wear resistance.

Other typical casting materials include:

Aluminum and magnesium alloys:

Aluminum is a difficult material to cast and needs to be alloyed with other metals, such as copper, magnesium, and zinc, as well as with silicon (up to 12ï 14%). In general, such alloys provide good fluidity, low shrinkage, and good resistance to cracking. The mechanical properties obtainable for aluminum alloys depend on the content of the alloying elements as well as on heat-treatment processes.

Magnesium is also a difficult material to cast in its pure form and is normally alloyed with aluminum, zinc, and zirconium. Such alloys can have excellent corrosion resistance and moderate strengths.

Copper-based alloys:

Copper may be alloyed with many different elements, including tin, lead, zinc, and nickel to yield, among others, a common engineering alloy known as bronze (80ï90% copper, 5ï20% tin, and less than 1ï2% of lead, zinc, phosphorous, nickel, and iron).

Steel castings:

These castings have isotropic uniformity of properties, regardless of direction of loading, when compared to cast iron. However, the strength and ductility of steel becomes a problem for the casting process, for example, causing high shrinkage rates. Low-carbon steel castings (< 0.2% carbon) can be found in numerous automotive applications, whereas high-carbon cast steels (0.5% carbon) are used for tool and die making.

Numerous advantages make casting a preferred manufacturing process over other metal fabrication processes. Intricate and complex geometry parts can be cast as single pieces, avoiding or minimizing subsequent forming and/or machining operations and occasionally even assembly operations; parts can be cast for mass production as well as for batch sizes of only several units and extremely large and heavy parts (thousands of kilograms) may be cast (as the only economically viable process of fabrication).

IV.1.1. Sand casting

Sand casting, the most widely used casting process, utilizes expendable sand molds to form complex metal parts that can be made of nearly any alloy. Because the sand mold must be destroyed in order to remove the part, called the casting, sand casting typically has a low production rate. The sand casting process involves the use of a furnace, metal, pattern, and sand mold. The metal is melted in the furnace and then ladled and poured into the cavity of the sand mold, which is formed by the pattern. The sand mold separates along a parting line and the solidified casting can be removed.

Sand casting is used to produce a wide variety of metal components with complex geometries. These parts can vary greatly in size and weight, ranging from a couple ounces to several tons. Some smaller sand cast parts include components as gears, pulleys, crankshafts, connecting rods, and propellers. Larger applications include housings for large equipment and heavy machine bases. Sand casting is also common in producing automobile components, such as engine blocks, engine manifolds, cylinder heads, and transmission cases.

In sand casting, the primary piece of equipment is the mold, which contains several components (Fig. 31).

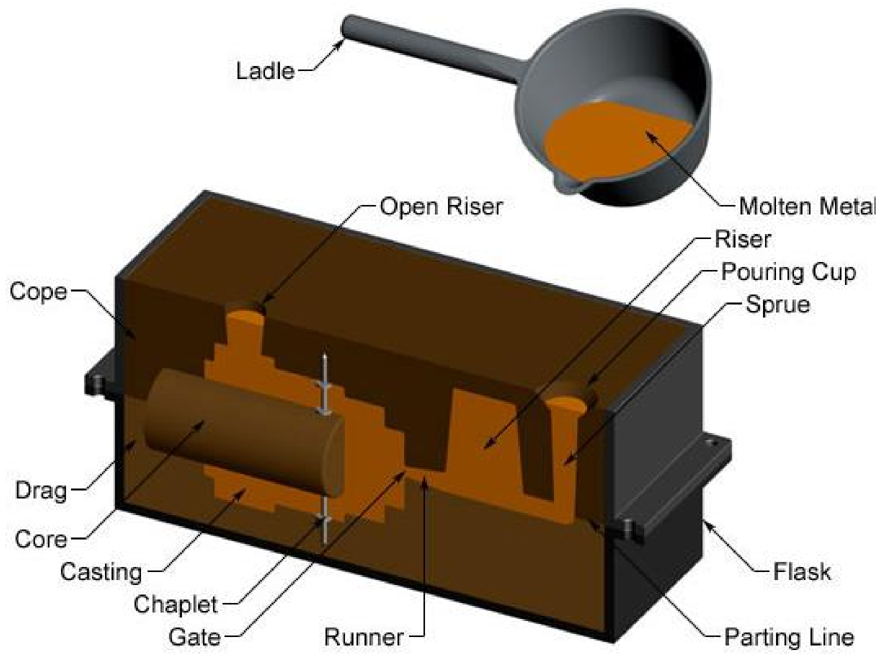


Fig. 31: Sand mold.

The mold is divided into two halves - the cope (upper half) and the drag (bottom half), which meet along a parting line. Both mold halves are contained inside a box, called a flask, which itself is divided along this parting line. The mold cavity is formed by packing sand around the pattern in each half of the flask. The sand can be packed by hand, but machines that use pressure or impact ensure even packing of the sand and require far less time, thus increasing the production rate. After the sand has been packed and the pattern is removed, a cavity will remain that forms the external shape of the casting. Some internal surfaces of the casting may be formed by cores.

Cores are additional pieces that form the internal holes and passages of the casting. Cores are typically made out of sand so that they can be shaken out of the casting, rather than require the necessary geometry to slide out. As a result, sand cores allow for the fabrication of many complex internal features. Each core is positioned in the mold before the molten metal is poured. In order to keep each core in place, the pattern has recesses called core prints where the core can be anchored in place. However, the core may still shift due to buoyancy in the molten metal. Further support is provided to the cores by chaplets. These are small metal pieces that are fastened between the core and the cavity surface. Chaplets must be made of a metal with a higher melting temperature than that of the metal being cast in order to maintain their structure. After solidification, the chaplets will have been cast inside the casting and the excess material of the chaplets that protrudes must be cut off.

In addition to the external and internal features of the casting, other features must be incorporated into the mold to accommodate the flow of molten metal. The molten metal is poured into a pouring basin, which is a large depression in the top of the sand mold. The molten metal funnels out of the bottom of this basin and down the main channel, called the sprue. The sprue then connects to a series of channels, called runners, which carries the molten metal into the cavity. At the end of each runner, the molten metal enters the cavity through a gate which controls the flow rate and minimizes turbulence. Often connected to the runner system are risers. Risers are chambers that fill with molten metal, providing an additional source of metal during solidification. When the casting cools, the molten metal will shrink and additional material is needed. A similar feature that aids in reducing shrinkage is an open riser. The first material to enter the cavity is allowed to pass completely through and enter the open riser. This strategy prevents early solidification of the molten metal and provides a source of material to compensate for shrinkage. Lastly, small channels are included that run from the cavity to the exterior of the mold. These channels act as venting holes to allow gases to escape the cavity. The porosity of the sand also allows air to escape, but additional vents are sometimes needed. The molten metal that flows through all of the channels (sprue, runners, and risers) will solidify attached to the casting and must be separated from the part after it is removed.

The process cycle for sand casting consists of six main stages, which are explained below.

Mold-making:

The first step in the sand casting process is to create the mold for the casting. In an expendable mold process, this step must be performed for each casting. A sand mold is formed by packing sand into each half of the mold. The sand is packed around the pattern, which is a replica of the external shape of the casting. When the pattern is removed, the cavity that will form the casting remains. Any internal features of the casting that cannot be formed by the pattern are formed by separate cores which are made of sand prior to the formation of the mold. Further details on mold-making will be described in the next section. The mold-making time includes positioning the pattern, packing the sand, and removing the pattern. The mold-making time is affected by the size of the part, the number of cores, and the type of sand mold. If the mold type requires heating or baking time, the mold-making time is substantially increased. Also, lubrication is often applied to the surfaces of the mold cavity in order to facilitate removal of the casting. The use of a lubricant also improves the flow the metal and can improve the surface finish of the casting. The lubricant that is used is chosen based upon the sand and molten metal temperature.

Clamping:

Once the mold has been made, it must be prepared for the molten metal to be poured. The surface of the mold cavity is first lubricated to facilitate the removal of the casting. Then, the cores are positioned and the mold halves are closed and securely clamped together. It is essential that the mold halves remain securely closed to prevent the loss of any material.

Pouring:

The molten metal is maintained at a set temperature in a furnace. After the mold has been clamped, the molten metal can be ladled from its holding container in the furnace and poured into the mold. The pouring can be performed manually or by an automated machine. Enough molten metal must be poured to fill the entire cavity and all channels in the mold. The filling time is very short in order to prevent early solidification of any one part of the metal.

Cooling:

The molten metal that is poured into the mold will begin to cool and solidify once it enters the cavity. When the entire cavity is filled and the molten metal solidifies, the final shape of the casting is formed. The mold cannot be opened until the cooling time has elapsed. The desired cooling time can be estimated based upon the wall thickness of the casting and the temperature of the metal. Most of the possible defects that can occur are a result of the solidification process. If some of the molten metal cools too quickly, the part may exhibit shrinkage, cracks, or incomplete sections. Preventative measures can be taken in designing both the part and the mold and will be explored in later sections.

Removal:

After the predetermined solidification time has passed, the sand mold can simply be broken, and the casting removed. This step, sometimes called shakeout, is typically performed by a vibrating machine that shakes the sand and casting out of the flask. Once removed, the casting will likely have some sand and oxide layers adhered to the surface. Shot blasting is sometimes used to remove any remaining sand, especially from internal surfaces, and reduce the surface roughness.

Trimming:

During cooling, the material from the channels in the mold solidifies attached to the part. This excess material must be trimmed from the casting either manually via cutting or sawing, or using a trimming press. The time required to trim the excess material can be estimated from the size of the casting's envelope. A larger casting will require a longer trimming time. The scrap material that results from this trimming is either discarded or reused in the sand casting process. However, the scrap material may need to be reconditioned to the proper chemical composition before it can be combined with non-recycled metal and reused.

IV.1.2. Investment casting

Investment casting is one of the oldest manufacturing processes, dating back thousands of years, in which molten metal is poured into an expendable ceramic mold. The mold is formed by using a wax pattern - a disposable piece in the shape of the desired part. The pattern is surrounded, or "invested", into ceramic slurry that hardens into the mold.

Investment casting is often referred to as "*lost-wax casting*" because the wax pattern is melted out of the mold after it has been formed. Lox-wax processes are one-to-one (one pattern creates one part), which increases production time and costs relative to other casting processes. However, since the mold is destroyed during the process, parts with complex geometries and intricate details can be created.

Investment casting can make use of most metals, most commonly using aluminum alloys, bronze alloys, magnesium alloys, cast iron, stainless steel, and tool steel. This process is beneficial for casting metals with high melting temperatures that cannot be molded in plaster or metal. Parts that are typically made by investment casting include those with complex geometry such as turbine blades or firearm components. High temperature applications are also common, which includes parts for the automotive, aircraft, and military industries.

Investment casting (Fig. 32) requires the use of a metal die, wax, ceramic slurry, furnace, molten metal, and any machines needed for sandblasting, cutting, or grinding.

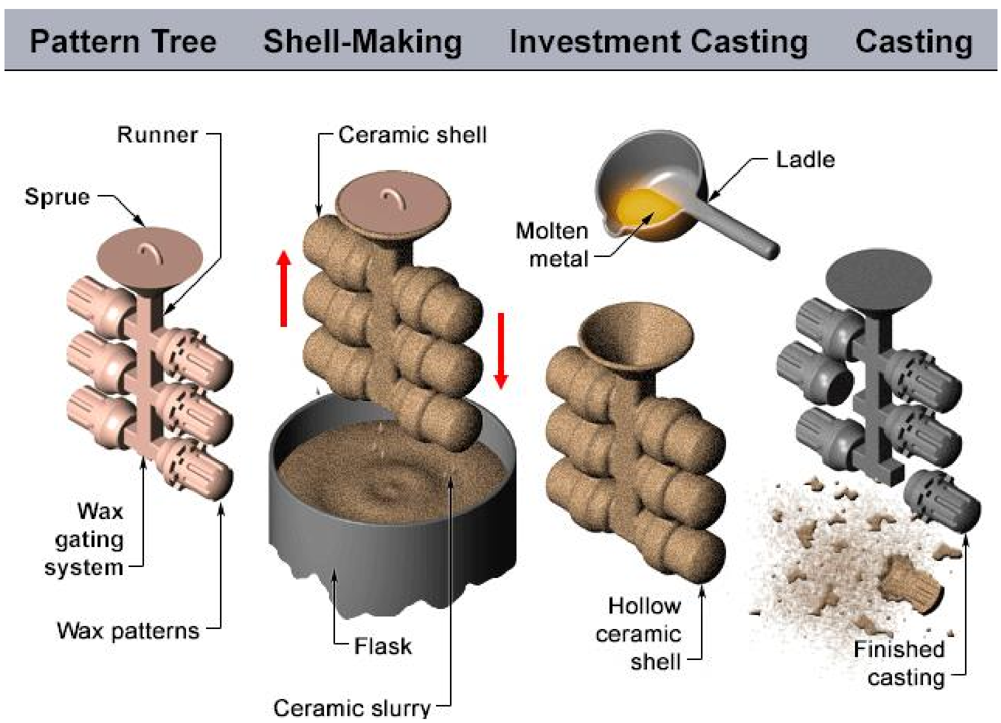


Fig.32: Investment casting process.

The process includes the following steps:

Pattern creation:

The wax patterns are typically injection molded into a metal die and are formed as one piece. Cores may be used to form any internal features on the pattern. Several of these patterns are attached to a central wax gating system (sprue, runners, and risers), to form a tree-like assembly. The gating system forms the channels through which the molten metal will flow to the mold cavity.

Mold creation:

This "pattern tree" is dipped into slurry of fine ceramic particles, coated with more coarse particles, and then dried to form a ceramic shell around the patterns and gating system.

This process is repeated until the shell is thick enough to withstand the molten metal it will encounter. The shell is then placed into an oven and the wax is melted out leaving a hollow ceramic shell that acts as a one-piece mold, hence the name "lost wax" casting.

Pouring:

The mold is preheated in a furnace to approximately 1000°C (1832°F) and the molten metal is poured from a ladle into the gating system of the mold, filling the mold cavity. Pouring is typically achieved manually under the force of gravity, but other methods such as vacuum or pressure are sometimes used.

Cooling:

After the mold has been filled, the molten metal is allowed to cool and solidify into the shape of the final casting. Cooling time depends on the thickness of the part, thickness of the mold, and the material used.

Casting removal:

After the molten metal has cooled, the mold can be broken and the casting removed. The ceramic mold is typically broken using water jets, but several other methods exist. Once removed, the parts are separated from the gating system by either sawing or cold breaking (using liquid nitrogen).

Finishing:

Often times, finishing operations such as grinding or sandblasting are used to smooth the part at the gates. Heat treatment is also sometimes used to harden the final part.

IV.1.3. Die Casting

Die casting is a manufacturing process that can produce geometrically complex metal parts through the use of reusable molds, called *dies*.

The die casting process involves the use of a furnace, metal, die casting machine, and die. The metal, typically a non-ferrous alloy such as aluminum or zinc, is melted in the furnace and then injected into the dies in the die casting machine.

There are two main types of die casting machines: hot chamber machines (used for alloys with low melting temperatures, such as zinc) and cold chamber machines (used for alloys with high melting temperatures, such as aluminum). The differences between these machines will be detailed in the sections on equipment and tooling. However, in both machines, after the molten metal is injected into the dies, it rapidly cools and solidifies into the final part, called the casting.

Hot chamber die casting machine:

Hot chamber machines (Fig. 33) are used for alloys with low melting temperatures, such as zinc, tin, and lead. The temperatures required to melt other alloys would damage the pump, which is in direct contact with the molten metal. The metal is contained in an open holding pot which is placed into a furnace, where it is melted to the necessary temperature. The molten metal then flows into a shot chamber through an inlet and a plunger, powered by hydraulic pressure, forces the molten metal through a gooseneck channel and into the die.

After the molten metal has been injected into the die cavity, the plunger remains down, holding the pressure while the casting solidifies. After solidification, the hydraulic system retracts the plunger and the part can be ejected by the clamping unit.

Prior to the injection of the molten metal, this unit closes and clamps the two halves of the die. When the die is attached to the die casting machine, each half is fixed to a large plate, called a platen.

The front half of the die, called the cover die, is mounted to a stationary platen and aligns with the gooseneck channel. The rear half of the die, called the ejector die, is mounted to a movable platen, which slides along the tie bars. The hydraulically powered clamping unit actuates clamping bars that push this platen towards the cover die and exert enough pressure to keep it closed while the molten metal is injected.

Following the solidification of the metal inside the die cavity, the clamping unit releases the die halves and simultaneously causes the ejection system to push the casting out of the open cavity. The die can then be closed for the next injection.

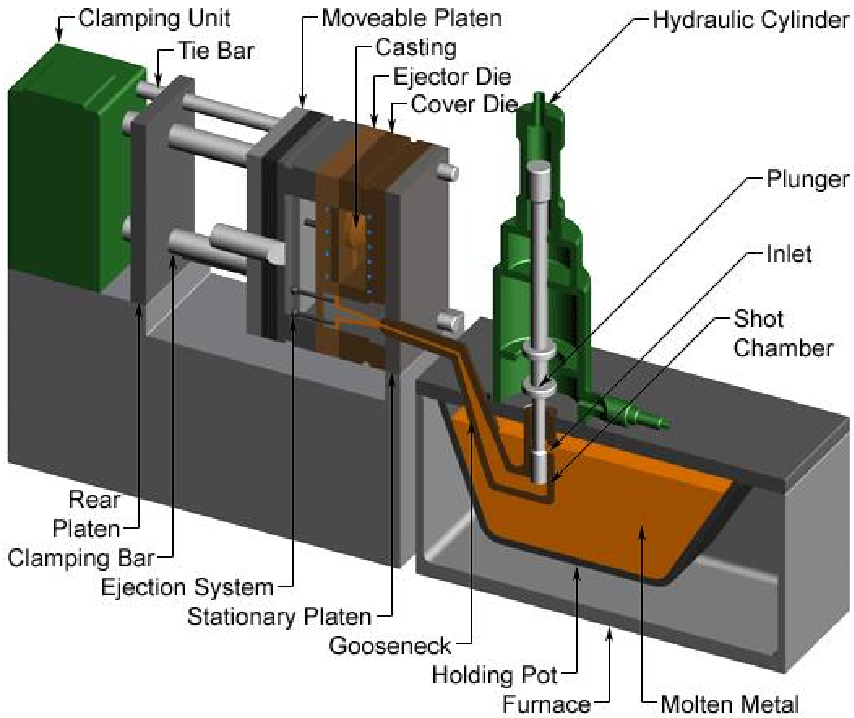


Fig.33: Hot chamber die casting machine.

Cold chamber die casting machine:

Cold chamber machines (Fig. 34) are used for alloys with high melting temperatures that cannot be cast in hot chamber machines because they would damage the pumping system. Such alloys include aluminum, brass, and magnesium. The molten metal is still contained in an open holding pot which is placed into a furnace, where it is melted to the necessary temperature. However, this holding pot is kept separate from the die casting machine and the molten metal is ladled from the pot for each casting, rather than being pumped.

The metal is poured from the ladle into the shot chamber through a pouring hole. The injection system in a cold chamber machine functions similarly to that of a hot chamber machine, however it is usually oriented horizontally and does not include a gooseneck channel. A plunger, powered by hydraulic pressure, forces the molten metal through the shot chamber and into the injection sleeve in the die.

After the molten metal has been injected into the die cavity, the plunger remains forward, holding the pressure while the casting solidifies. After solidification, the hydraulic system retracts the plunger and the part can be ejected by the clamping unit. The clamping unit and mounting of the dies is identical to the hot chamber machine.

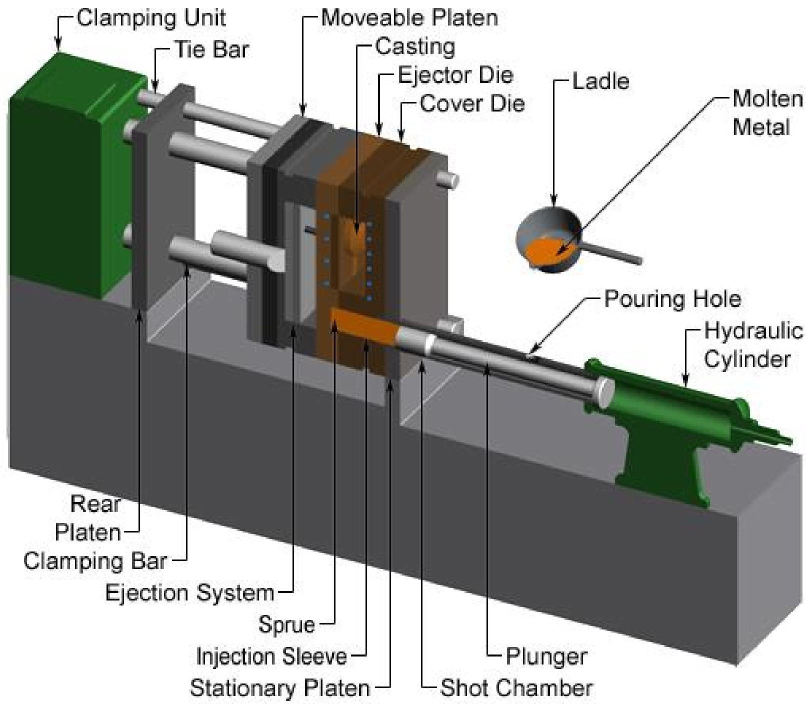


Fig.34: Cold chamber die casting machine.

The castings that are created in this process can vary greatly in size and weight. One common application of die cast parts are housings - thin-walled enclosures, often requiring many ribs and bosses on the interior. Metal housings for a variety of appliances and equipment are often die cast. Several automobile components are also manufactured using die casting, including pistons, cylinder heads, and engine blocks. Other common die cast parts include propellers, gears, bushings, pumps, and valves.

The process cycle for die casting consists of five main stages, which are explained below. The total cycle time is very short, typically between 2 seconds and 1 minute.

Clamping:

The first step is the preparation and clamping of the two halves of the die. Each die half is first cleaned from the previous injection and then lubricated to facilitate the ejection of the next part. The lubrication time increases with part size, as well as the number of cavities and side-cores. Also, lubrication may not be required after each cycle, but after 2 or 3 cycles, depending upon the material. After lubrication, the two die halves, which are attached inside the die casting machine, are closed and securely clamped together. Sufficient force must be applied to the die to keep it securely closed while the metal is injected. The time required to close and clamp the die is dependent upon the machine - larger machines (those with greater clamping forces) will require more time. This time can be estimated from the dry cycle time of the machine.

Injection:

The molten metal, which is maintained at a set temperature in the furnace, is next transferred into a chamber where it can be injected into the die. The method of transferring the molten metal is dependent upon the type of die casting machine, whether a hot chamber or cold chamber machine is being used. The difference in this equipment will be detailed in the next section. Once transferred, the molten metal is injected at high pressures into the die. This pressure holds the molten metal in the dies during solidification. The amount of metal that is injected into the die is referred to as the shot. The injection time is the time required for the molten metal to fill all of the channels and cavities in the die. This time is very short, typically less than 0.1 seconds, in order to prevent early solidification of any one part of the metal. The proper injection time can be determined by the thermodynamic properties of the material, as well as the wall thickness of the casting. A greater wall thickness will require a longer injection time. In the case where a cold chamber die casting machine is being used, the injection time must also include the time to manually ladle the molten metal into the shot chamber.

Cooling:

The molten metal that is injected into the die will begin to cool and solidify once it enters the die cavity. When the entire cavity is filled and the molten metal solidifies, the final shape of the casting is formed. The die cannot be opened until the cooling time has elapsed and the casting is solidified. The cooling time can be estimated from several thermodynamic properties of the metal, the maximum wall thickness of the casting, and the complexity of the die. A greater wall thickness will require a longer cooling time. The geometric complexity of the die also requires a longer cooling time because the additional resistance to the flow of heat.

Ejection:

After the predetermined cooling time has passed, the die halves can be opened and an ejection mechanism can push the casting out of the die cavity. The time to open the die can be estimated from the dry cycle time of the machine and the ejection time is determined by the size of the casting's envelope and should include time for the casting to fall free of the die. The ejection mechanism must apply some force to eject the part because during cooling the part shrinks and adheres to the die. Once the casting is ejected, the die can be clamped shut for the next injection.

Trimming:

During cooling, the material in the channels of the die will solidify attached to the casting. This excess material, along with any flash that has occurred, must be trimmed from the casting either manually via cutting or sawing, or using a trimming press. The time required to trim the excess material can be estimated from the size of the casting's envelope. The scrap material that results from this trimming is either discarded or can be reused in the die casting process. Recycled material may need to be reconditioned to the proper chemical composition before it can be combined with non-recycled metal and reused in the die casting process.

IV.1.4. Centrifugal Casting

Centrifugal casting, sometimes called rotocasting, is a metal casting process that uses centrifugal force to form cylindrical parts. This differs from most metal casting processes, which use gravity or pressure to fill the mold. In centrifugal casting, a permanent mold made from steel, cast iron, or graphite is typically used. However, the use of expendable sand molds is also possible. The casting process is usually performed on a horizontal centrifugal casting machine (Fig. 35) (vertical machines are also available) and includes the following steps:

Mold preparation

The walls of a cylindrical mold are first coated with a refractory ceramic coating, which involves a few steps (application, rotation, drying, and baking). Once prepared and secured, the mold is rotated about its axis at high speeds (300-3000 RPM), typically around 1000 RPM.

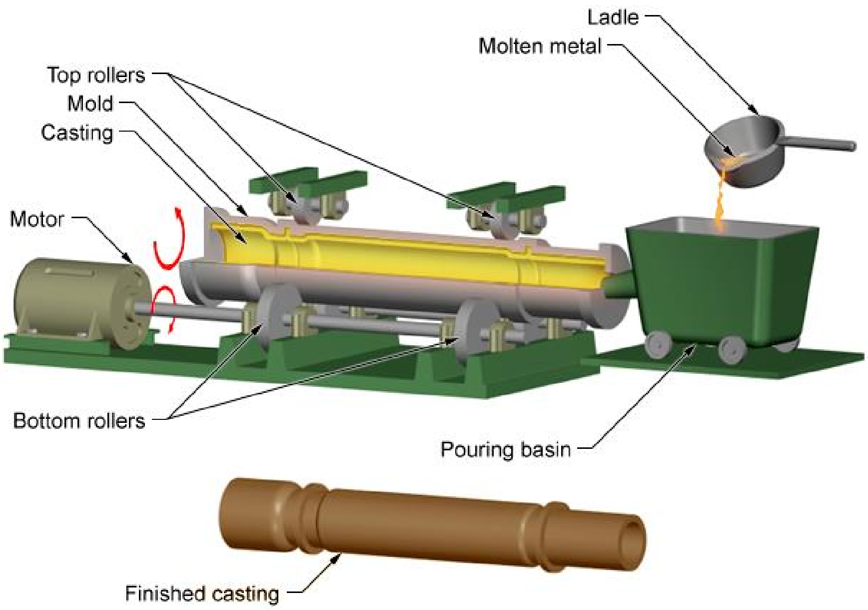


Fig.35: Centrifugal casting.

Pouring:

Molten metal is poured directly into the rotating mold, without the use of runners or a gating system. The centrifugal force drives the material towards the mold walls as the mold fills.

Cooling:

With all of the molten metal in the mold, the mold remains spinning as the metal cools. Cooling begins quickly at the mold walls and proceeds inwards.

Casting removal:

After the casting has cooled and solidified, the rotation is stopped and the casting can be removed.

Finishing:

While the centrifugal force drives the dense metal to the mold walls, any less dense impurities or bubbles flow to the inner surface of the casting. As a result, secondary processes such as machining, grinding, or sand-blasting, are required to clean and smooth the inner diameter of the part.

Centrifugal casting is used to produce axi-symmetric parts, such as cylinders or disks, which are typically hollow. Due to the high centrifugal forces, these parts have a very fine grain on the outer surface and possess mechanical properties approximately 30% greater than parts formed with static casting methods. These parts may be cast from ferrous metals such as low alloy steel, stainless steel, and iron, or from non-ferrous alloys such as aluminum, bronze, copper, magnesium, and nickel. Centrifugal casting is performed in wide variety of industries, including aerospace, industrial, marine, and power transmission. Typical parts include bearings, bushings, coils, cylinder liners, nozzles, pipes/tubes, pressure vessels, pulleys, rings, and wheels.

IV.1.5. Permanent Mold Casting

Permanent mold casting (Fig.36) is a metal casting process that shares similarities to both sand casting and die casting. As in sand casting, molten metal is poured into a mold which is clamped shut until the material cools and solidifies into the desired part shape. However, sand casting uses an expendable mold which is destroyed after each cycle.

Permanent mold casting, like die casting, uses a metal mold (die) that is typically made from steel or cast iron and can be reused for several thousand cycles. Because the molten metal is poured into the die and not forcibly injected, permanent mold casting is often referred to as gravity die casting.

Permanent mold casting is typically used for high-volume production of small, simple metal parts with uniform wall thickness. Non-ferrous metals are typically used in this process, such as aluminum alloys, magnesium alloys, and copper alloys. However, irons and steels can also be cast using graphite molds.

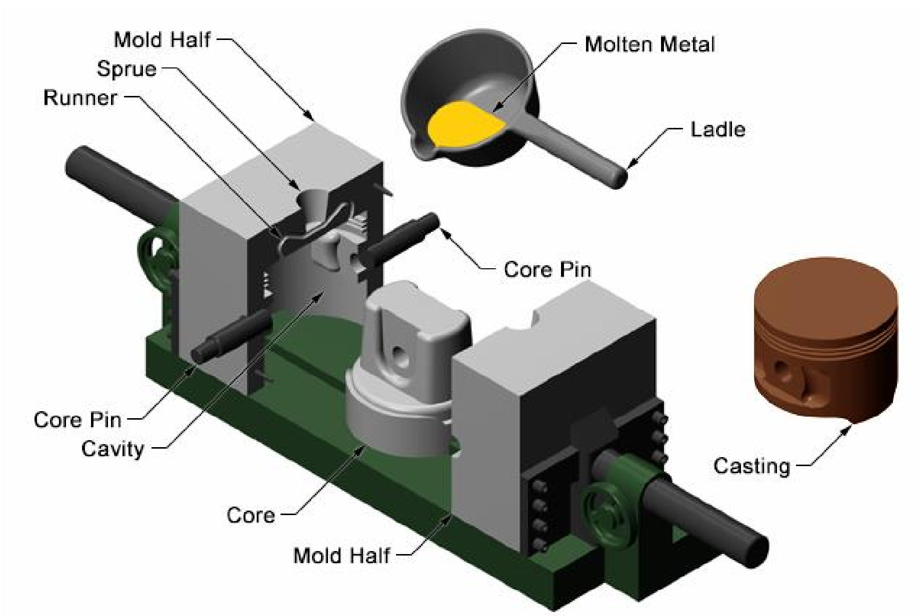


Fig.36: Permanent mold casting.

The permanent mold casting process consists of the following steps:

Mold preparation

First, the mold is pre-heated to around 300-500°F (150-260°C) to allow better metal flow and reduce defects. Then, a ceramic coating is applied to the mold cavity surfaces to facilitate part removal and increase the mold lifetime.

Mold assembly

The mold consists of at least two parts - the two mold halves and any cores used to form complex features. Such cores are typically made from iron or steel, but expendable sand cores are sometimes used. In this step, the cores are inserted and the mold halves are clamped together.

Pouring:

The molten metal is poured at a slow rate from a ladle into the mold through a sprue at the top of the mold. The metal flows through a runner system and enters the mold cavity.

Cooling:

The molten metal is allowed to cool and solidify in the mold.

Mold opening:

After the metal has solidified, the two mold halves are opened and the casting is removed.

Trimming:

During cooling, the metal in the runner system and sprue solidify attached to the casting. This excess material is now cut away.

Common permanent mold parts include gears and gear housings, pipe fittings, and other automotive and aircraft components such as pistons, impellers, and wheels.

IV.2. Machining

Machining is a term used to describe a variety of material removal processes in which a cutting tool removes unwanted material from a work-piece to produce the desired shape. The work-piece is typically cut from a larger piece of stock, which is available in a variety of standard shapes, such as flat sheets, solid bars, hollow tubes, and shaped beams. Machining can also be performed on an existing part, such as a casting or forging.

Parts that are machined from a pre-shaped work-piece are typically cubic or cylindrical in their overall shape, but their individual features may be quite complex. Machining can be used to create a variety of features including holes, slots, pockets, flat surfaces, and even complex surface contours. Also, while machined parts are typically metal, almost all materials can be machined, including metals, plastics, composites, and wood. For these reasons, machining is often considered the most common and versatile of all manufacturing processes.

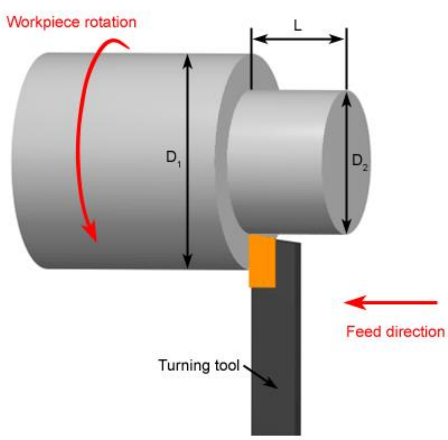
As a material removal process, machining is inherently not the most economical choice for a primary manufacturing process. Material, which has been paid for, is cut away and discarded to achieve the final part. Also, despite the low setup and tooling costs, long machining times may be required and therefore be cost prohibitive for large quantities. As a result, machining is most often used for limited quantities as in the fabrication of prototypes or custom tooling for other manufacturing processes. Machining is also very commonly used as a secondary process, where minimal material is removed and the cycle time is short. Due to the high tolerance and surface finishes that machining offers, it is often used to add or refine precision features to an existing part or smooth a surface to a fine finish.

As mentioned above, machining includes a variety of processes that each removes material from an initial work-piece or part. The most common material removal processes, sometimes referred to as conventional or traditional machining, are those that mechanically cut away small chips of material using a sharp tool. Non-conventional machining processes may use chemical or thermal means of removing material.

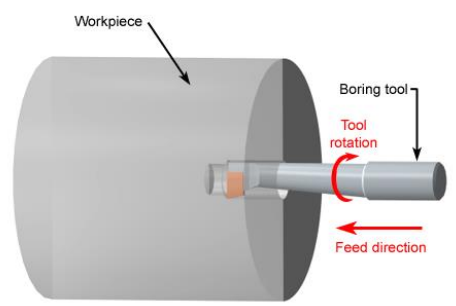
Conventional machining processes are often placed in three categories: single point cutting, multi-point cutting and abrasive machining. Each process in these categories is uniquely defined by the type of cutting tool used and the general motion of that tool and the work-piece. However, within a given process a variety of operations can be performed, each utilizing a specific type of tool and cutting motion. The machining of a part will typically require a variety of operations that are performed in a carefully planned sequence to create the desired features.

IV.2.1. Single point cutting

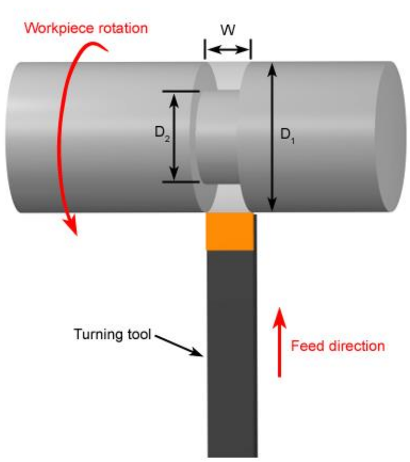
Single point cutting refers to using a cutting tool with a single sharp edge that is used to remove material from the work-piece. The most common single point cutting process is *turning*, in which the work-piece rotates and the cutting tool feeds into the work-piece, cutting away material. Turning is performed on a lathe or turning machine and produces cylindrical parts that may have external or internal features. Turning operations such as turning, boring, facing, grooving, cut-off (parting), and thread cutting (Fig. 37) allow for a wide variety of features to be machined, including slots, tapers, threads, flat surfaces, and complex contours. Other single point cutting processes exist that do not require the work-piece to rotate, such as *planing* and *shaping*.



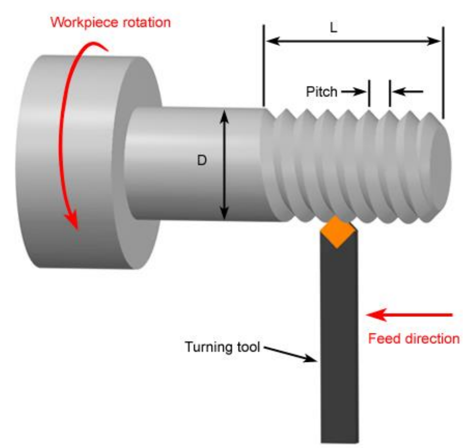
Turning



Boring



Grooving



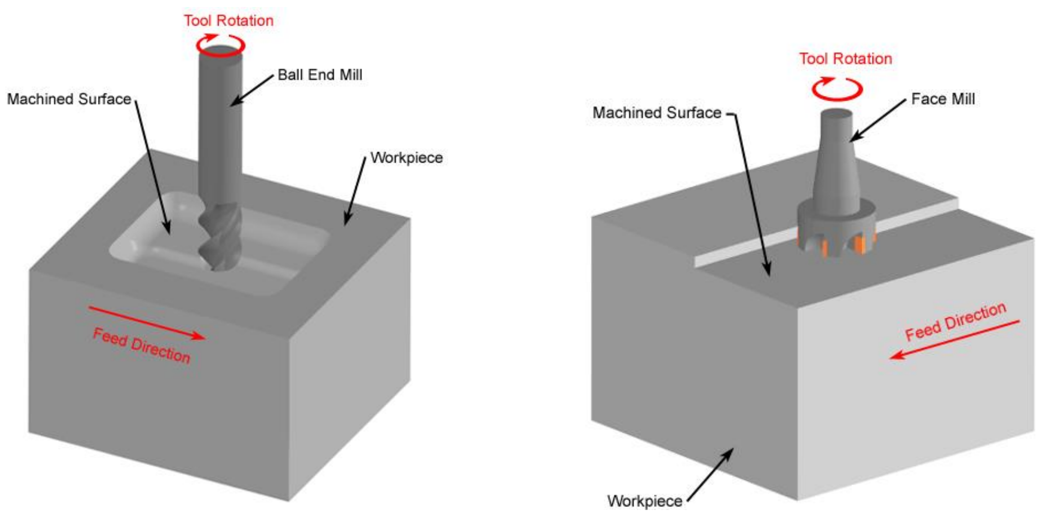
Thread cutting

Fig. 37: Turning operations

IV.2.2. Multi-point cutting

Multi-point cutting refers to using a cutting tool with many sharp teeth that moves against the work-piece to remove material. The two most common multi-point cutting processes are *milling* and *drilling* (Fig. 38). In both processes, the cutting tool is cylindrical with sharp teeth around its perimeter and rotates at high speeds.

In *milling*, the work-piece is fed into the rotating tool along different paths and depths to create a variety of features. Performed on a milling machine, milling operations such as end milling, chamfer milling, and face milling are used to create slots, chamfers, pockets, flat surfaces, and complex contours. Milling machines can also perform drilling and other hole-making operations as well.



End milling Face milling

Fig. 38: Milling processes

In *drilling*, the rotating tool is fed vertically into the stationary work-piece to create a hole. A drill press is specifically designed for drilling, but milling machines and turning machines can also perform this process. Drilling operations such as counterboring, countersinking, reaming, and tapping (Fig.39) can be used to create recessed holes, high precision holes, and threaded holes. Other multi-point cutting processes exist that do not require the tool to rotate, such as broaching and sawing.

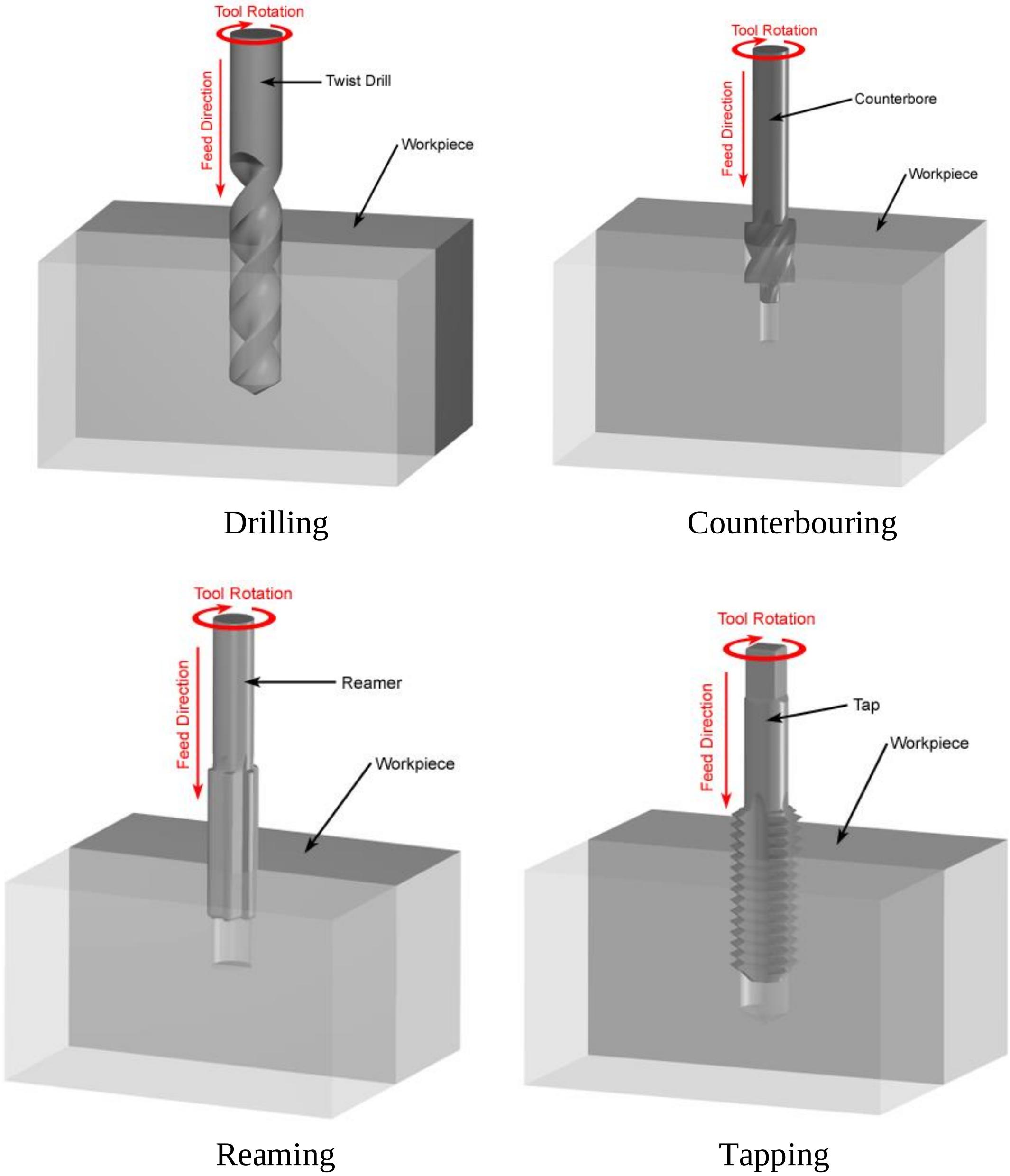


Fig.39: Drilling operations

IV.2.3. Abrasive machining

Abrasive machining refers to using a tool formed of tiny abrasive particles to remove material from a work-piece. Abrasive machining is considered a mechanical process like milling or turning because each particle cuts into the work-piece removing a small chip of material. While typically used to improve the surface finish of a part, abrasive machining can still be used to shape a work-piece and form features.

The most common abrasive machining process is grinding, in which the cutting tool is abrasive grains bonded into a wheel that rotates against the work-piece. Grinding may be performed on a surface grinding machine which feeds the work-piece into the cutting tool, or a cylindrical grinding machine which rotates the work-piece as the cutting tool feeds into it. Other abrasive machining processes use particles in other ways, such as attached to a soft material or suspended in a liquid. Such processes include honing, lapping, ultrasonic machining, and abrasive jet machining.

IV.3. Sheet Metal Fabrication

Sheet metal fabrication is a classification of manufacturing processes that shape a piece of sheet metal into the desired part through material removal and/or material deformation.

Sheet metal, which acts as the work-piece in these processes, is one of the most common forms of raw material stock. The thickness of a piece of sheet metal is often referred to as its gauge, a number typically ranging from 3 to 38. A higher gauge indicates a thinner piece of sheet metal, with exact dimensions that depend on the material. Sheet metal stock is available in a wide variety of materials, which include the following: Aluminum, Brass, Bronze, Copper, Magnesium, Nickel, Stainless steel, Steel, Tin, Titanium, Zinc.

Sheet metal can be *cut*, *bent*, and *stretched* into a nearly any shape. Material removal processes can create holes and cutouts in any 2D geometric shape. Deformation processes can bend the sheet numerous times to different angles or stretch the sheet to create complex contours. The size of sheet metal parts can range from a small washer or bracket, to midsize enclosures for home appliances, to large airplane wings. These parts are found in a variety of industries.

Sheet metal fabrication processes can mostly be placed into two categories: *forming* and *cutting*.

Forming processes are those in which the applied force causes the material to plastically deform, but not to fail. Such processes are able to bend or stretch the sheet into the desired shape.

Cutting processes are those in which the applied force causes the material to fail and separate, allowing the material to be cut or removed. Most cutting processes are performed by applying a great enough shearing force to separate the material, and are therefore sometimes referred to as shearing processes. Other cutting processes remove material by using heat or abrasion, instead of shearing forces.

IV.3.1. Sheet Metal Forming

Sheet metal forming processes are those in which force is applied to a piece of sheet metal to modify its geometry rather than remove any material. The applied force stresses the metal beyond its yield strength, causing the material to plastically deform, but not to fail. By doing so, the sheet can be bent or stretched into a variety of complex shapes. Sheet metal forming processes include: *bending, roll forming, spinning, deep drawing, and stretch forming*.

- ***Bending***

Bending is a metal forming process in which a force is applied to a piece of sheet metal, causing it to bend at an angle and form the desired shape. A bending operation causes deformation along one axis, but a sequence of several different operations can be performed to create a complex part. Bent parts can be quite small, such as a bracket, or real large, such as enclosures or chassis. A bend can be characterized by several different parameters, shown in Fig. 40:

- *Bend line* - The straight line on the surface of the sheet, on either side of the bend, which defines the end of the level flange and the start of the bend.
- *Outside mold line* - The straight line where the outside surfaces of the two flanges would meet, were they to continue. This line defines the edge of a mold that would bind the bent sheet metal.
- *Flange length* - The length of either of the two flanges, extending from the edge of the sheet to the bend line.
- *Mold line distance* - The distance from either end of the sheet to the outside mold line.
- *Setback* - The distance from either bend line to the outside mold line. Also equal to the difference between the mold line distance and the flange length.

- *Bend axis* - The straight line that defines the center around which the sheet metal is bent.
- *Bend length* - The length of the bend, measured along the bend axis.
- *Bend radius* - The distance from the bend axis to the inside surface of the material, between the bend lines. Sometimes specified as the inside bend radius. The outside bend radius is equal to the inside bend radius plus the sheet thickness.
- *Bend angle* - The angle of the bend, measured between the bent flange and its original position, or as the included angle between perpendicular lines drawn from the bend lines.
- *Bevel angle* - The complimentary angle to the bend angle.

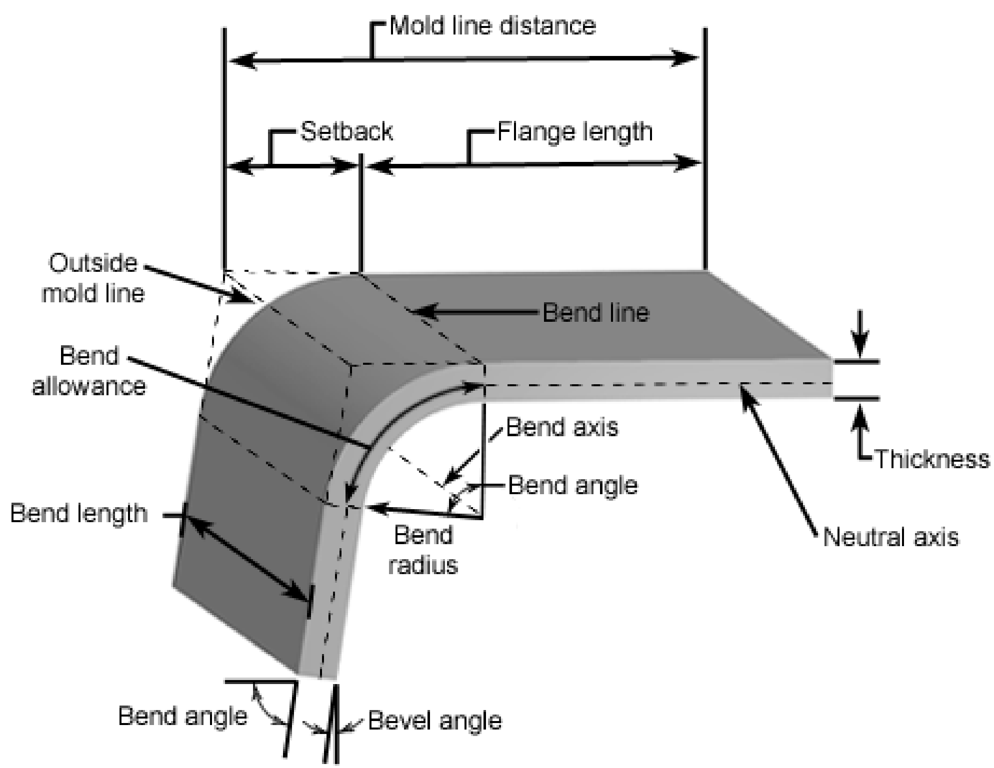


Fig. 40: Bending parameters

The act of bending results in both tension and compression in the sheet metal. The outside portion of the sheet will undergo tension and stretch to a greater length, while the inside portion experiences compression and shortens. The neutral axis is the boundary line inside the sheet metal, along which no tension or compression forces are present. As a result, the length of this axis remains constant.

When bending a piece of sheet metal, the residual stresses in the material will cause the sheet to springback slightly after the bending operation. Due to this elastic recovery, it is necessary to over-bend the sheet a precise amount to achieve the desired bend radius and bend angle. The final bend radius will be greater than initially formed and the final bend angle will be smaller. The ratio of the final bend angle to the initial bend angle is defined as the springback factor, K_S. The amount of springback depends upon several factors, including the material, bending operation, and the initial bend angle and bend radius.

Bending is typically performed on a machine called a press brake (Fig.41), which can be manually or automatically operated. For this reason, the bending process is sometimes referred to as *press brake forming*. Press brakes are available in a range of sizes (commonly 20-200 tons) in order to best suit the given application. A press brake contains an upper tool called the punch and a lower tool called the die, between which the sheet metal is located. The sheet is carefully positioned over the die and held in place by the back gauge while the punch lowers and forces the sheet to bend. In an automatic machine, the punch is forced into the sheet under the power of a hydraulic ram. The bend angle achieved is determined by the depth to which the punch forces the sheet into the die.

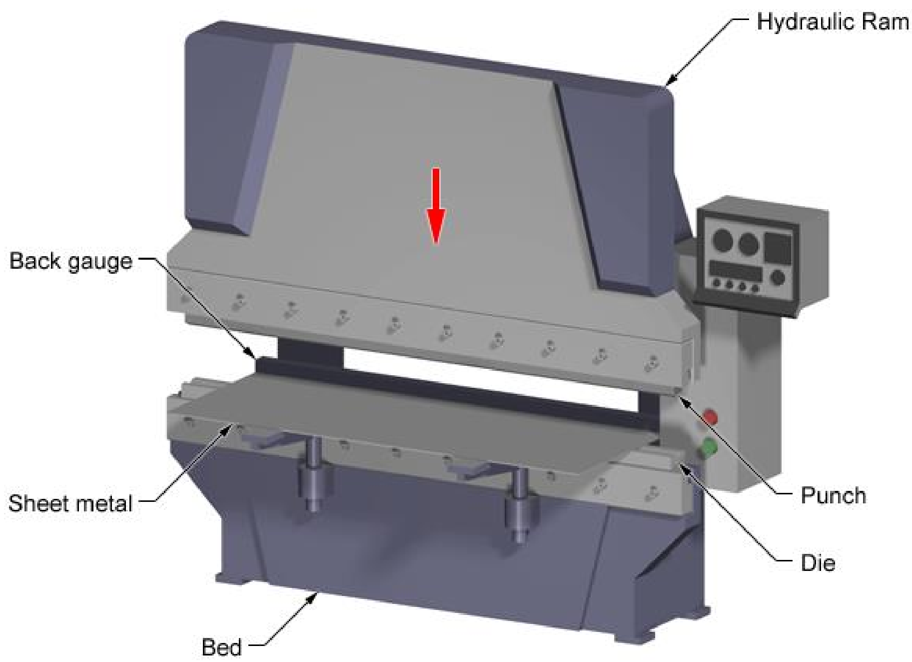


Fig. 41: Press brake

- ***Roll forming***

Roll forming, sometimes spelled roll-forming, is a metal forming process in which sheet metal is progressively shaped through a series of bending operations. The process is performed on a roll forming line (Fig. 42) in which the sheet metal stock is fed through a series of roll stations. Each station has a roller, referred to as a roller die, positioned on both sides of the sheet. The shape and size of the roller die may be unique to that station, or several identical roller dies may be used in different positions. The roller dies may be above and below the sheet, along the sides, at an angle, etc.

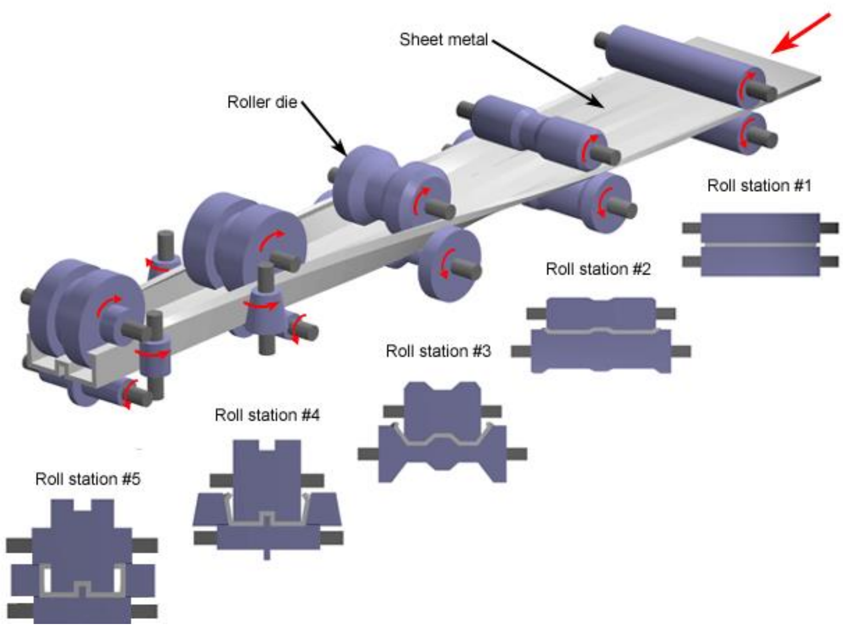


Fig. 42: Roll forming line.

As the sheet is forced through the roller dies in each roll station, it plastically deforms and bends. Each roll station performs one stage in the complete bending of the sheet to form the desired part. The roller dies are lubricated to reduce friction between the die and the sheet, thus reducing the tool wear. Also, lubricant can allow for a higher production rate, which will also depend on the material thickness, number of roll stations, and radius of each bend. The roll forming line can also include other sheet metal fabrication operations before or after the roll forming, such as punching or shearing.

The roll forming process can be used to form a sheet into a wide variety of cross-section profiles. An open profile is most common, but a closed tube-like shape can be created as well. Because the final form is achieved through a series of bends, the part does not require a uniform or symmetric cross-section along its length.

Typical roll formed parts include panels, tracks, shelving, etc. These parts are commonly used in industrial and commercial buildings for roofing, lighting, storage units, and HVAC applications.

- ***Spinning***

Spinning, sometimes called spin forming, is a metal forming process used to form cylindrical parts by rotating a piece of sheet metal while forces are applied to one side. A sheet metal disc is rotated at high speeds while rollers press the sheet against a tool, called a mandrel, to form the shape of the desired part. Spun metal parts have a rotationally symmetric, hollow shape, such as a cylinder, cone, or hemisphere. Examples include cookware, hubcaps, satellite dishes, rocket nose cones, and musical instruments.

Spinning is typically performed on a manual or CNC lathe and requires a blank, mandrel, and roller tool (Fig. 43).

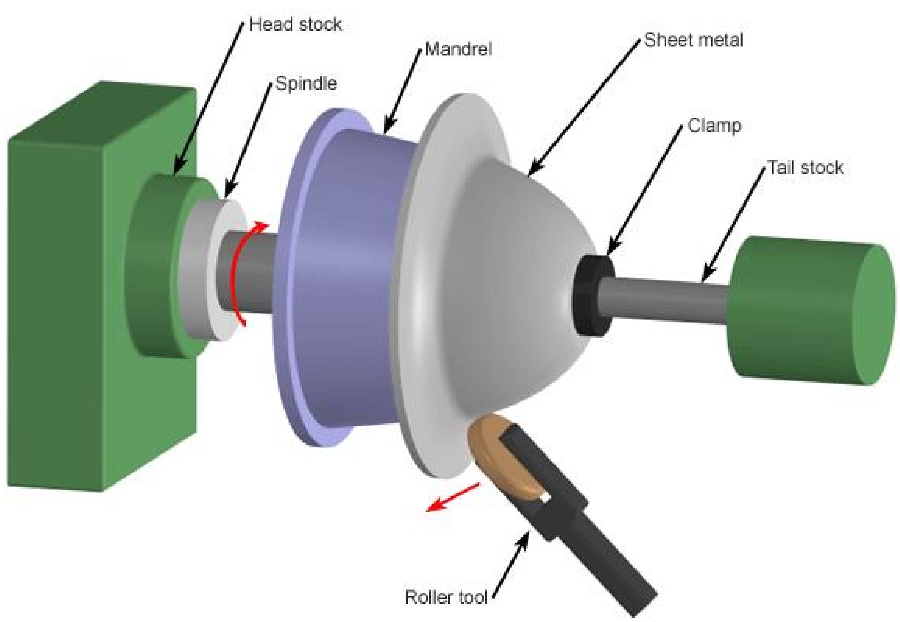


Fig. 43: Spin forming lathe

The blank is the disc-shaped piece of sheet metal that is pre-cut from sheet stock and will be formed into the part. The mandrel is a solid form of the internal shape of the part, against which the blank will be pressed. For more complex parts, such as those with reentrant surfaces, multi-piece mandrels can be used. Because the mandrel does not experience much wear in this process, it can be made from wood or plastic. However, high volume production typically utilizes a metal mandrel. The mandrel and blank are clamped together and secured between the headstock and tailstock of the lathe to be rotated at high speeds by the spindle. While the blank and mandrel rotate, force is applied to the sheet by a tool, causing the sheet to bend and form around the mandrel. The tool may make several passes to complete the shaping of the sheet. This tool is usually a roller wheel attached to a lever. Rollers are available in different diameters and thicknesses and are usually made from steel or brass. The rollers are inexpensive and experience little wear allowing for low volume production of parts.

- ***Deep Drawing***

Deep drawing is a metal forming process in which sheet metal is stretched into the desired part shape. A tool pushes downward on the sheet metal, forcing it into a die cavity in the shape of the desired part (Fig. 44).

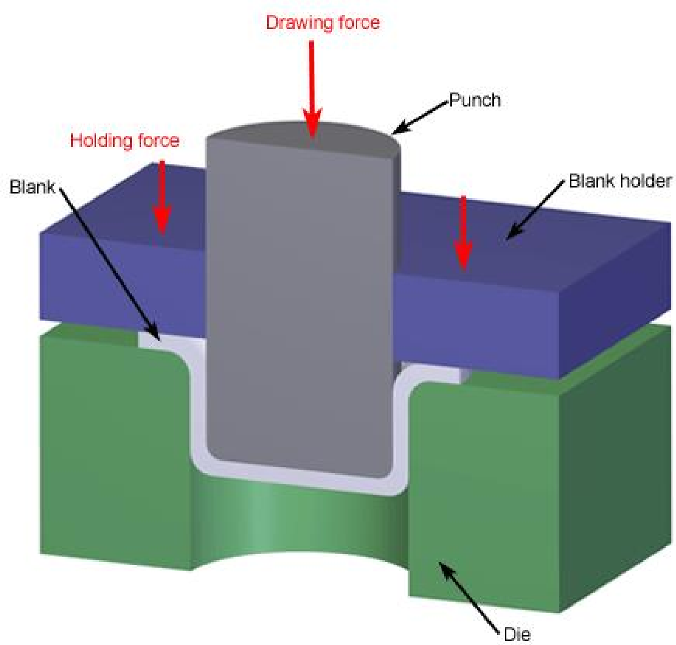


Fig. 44: Deep drawing process

The tensile forces applied to the sheet cause it to plastically deform into a cup-shaped part. Deep drawn parts are characterized by a depth equal to more than half of the diameter of the part. These parts can have a variety of cross sections with straight, tapered, or even curved walls, but cylindrical or rectangular parts are most common. Deep drawing is most effective with ductile metals, such as aluminum, brass, copper, and mild steel. Examples of parts formed with deep drawing include automotive bodies and fuel tanks, cans, cups, kitchen sinks, and pots and pans.

The deep drawing process requires a blank, blank holder, punch, and dies. The blank is a piece of sheet metal, typically a disc or rectangle, which is pre-cut from stock material and will be formed into the part. The blank is clamped down by the blank holder over the die, which has a cavity in the external shape of the part. A tool called a punch moves downward into the blank and draws, or stretches, the material into the die cavity. The movement of the punch is usually hydraulically powered to apply enough force to the blank. Both the die and punch experience wear from the forces applied to the sheet metal and are therefore made from tool steel or carbon steel.

The process of drawing the part sometimes occurs in a series of operations, called draw reductions. In each step, a punch forces the part into a different die, stretching the part to a greater depth each time. After a part is completely drawn, the punch and blank holder can be raised and the part removed from the die. The portion of the sheet metal that was clamped under the blank holder may form a flange around the part that can be trimmed off.

- ***Stretch Forming***

Stretch forming is a metal forming process in which a piece of sheet metal is stretched and bent simultaneously over a die in order to form large contoured parts. Stretch forming is performed on a stretch press (Fig. 45), in which a piece of sheet metal is securely gripped along its edges by gripping jaws. The gripping jaws are each attached to a carriage that is pulled by pneumatic or hydraulic force to stretch the sheet. The tooling used in this process is a stretch form block, called a form die, which is a solid contoured piece against which the sheet metal will be pressed. The most common stretch presses are oriented vertically, in which the form die rests on a press table that can be raised into the sheet by a hydraulic ram. As the form die is driven into the sheet, which is gripped tightly at its edges, the tensile forces increase and the sheet plastically deforms into a new shape. Horizontal stretch presses mount the form die sideways on a stationary press table, while the gripping jaws pull the sheet horizontally around the form die.

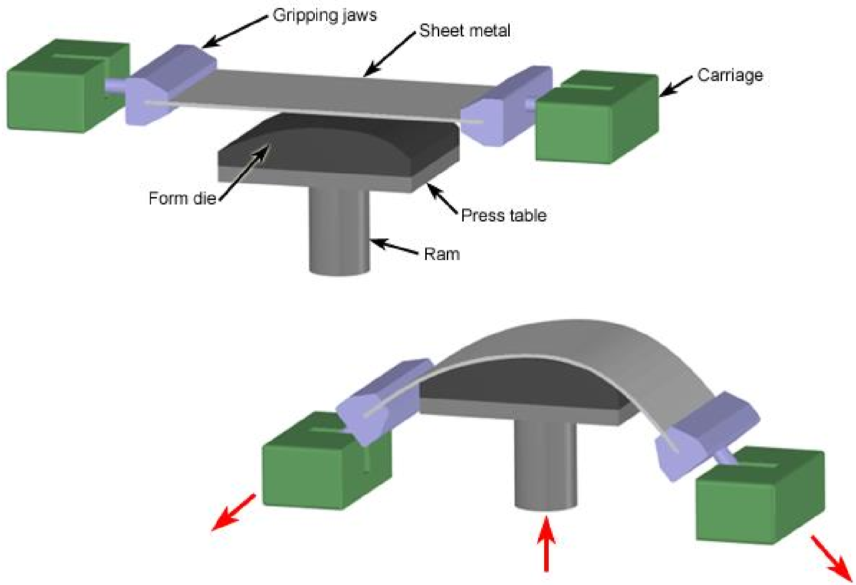


Fig. 45: Stretch forming process

Stretch formed parts are typically large and possess large radius bends. The shapes that can be produced vary from a simple curved surface to complex non-uniform cross sections. Stretch forming is capable of shaping parts with very high accuracy and smooth surfaces. Ductile materials are preferable, the most commonly used being aluminum, steel, and titanium. Typical stretch formed parts are large curved panels such as door panels in cars or wing panels on aircraft. Other stretch formed parts can be found in window frames and enclosures

IV.3.2. Sheet Metal Cutting (Shearing)

Cutting processes are those in which a piece of sheet metal is separated by applying a great enough force to cause the material to fail. The most common cutting processes are performed by applying a shearing force, and are therefore sometimes referred to as shearing processes. When a great enough shearing force is applied, the shear stress in the material will exceed the ultimate shear strength and the material will fail and separate at the cut location. This shearing force is applied by two tools, one above and one below the sheet.

Whether these tools are a punch and die or upper and lower blades, the tool above the sheet delivers a quick downward blow to the sheet metal that rests over the lower tool. A small clearance is present between the edges of the upper and lower tools, which facilitates the fracture of the material. The size of this clearance is typically 2-10% of the material thickness and depends upon several factors, such as the specific shearing process, material, and sheet thickness.

A variety of cutting processes that utilize shearing forces exist to separate or remove material from a piece of sheet stock in different ways. Each process is capable of forming a specific type of cut, some with an open path to separate a portion of material and some with a closed path to cutout and remove that material. By using many of these processes together, sheet metal parts can be fabricated with cutouts and profiles of any 2D geometry.

Such cutting processes include: *shearing*, *blanking,* and *punching* (piercing, slotting, perforating, notching, nibbling, lancing, slitting, parting, cutoff, trimming, shaving, dinking).

- ***Shearing***

The shearing process is performed on a shear machine (Fig. 46), often called a squaring shear or power shear, that can be operated manually (by hand or foot) or by hydraulic, pneumatic, or electric power.

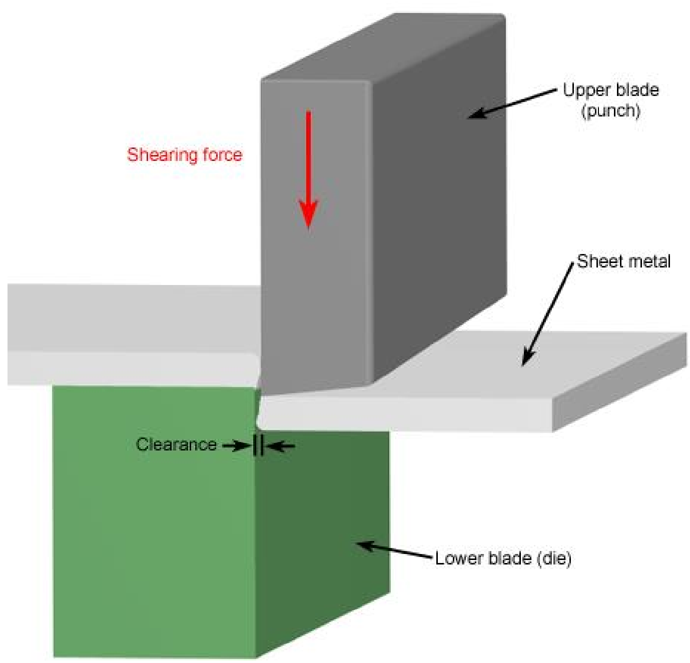


Fig. 46: Shearing process

A typical shear machine includes a table with support arms to hold the sheet, stops or guides to secure the sheet, upper and lower straight-edge blades, and a gauging device to precisely position the sheet. The sheet is placed between the upper and lower blade, which are then forced together against the sheet, cutting the material. In most devices, the lower blade remains stationary while the upper blade is forced downward. The upper blade is slightly offset from the lower blade, approximately 5-10% of the sheet thickness. Also, the upper blade is usually angled so that the cut progresses from one end to the other, thus reducing the required force.

The blades used in these machines typically have a square edge rather than a knife-edge and are available in different materials, such as low alloy steel and high-carbon steel.

Most commonly, shearing is used to cut a sheet parallel to an existing edge which is held square, but angled cuts can be made as well. For this reason, shearing is primarily used to cut sheet stock into smaller sizes in preparation for other processes.

- ***Blanking***

Blanking is a cutting process in which a piece of sheet metal is removed from a larger piece of stock by applying a great enough shearing force. In this process, the piece removed, called the blank, is not scrap but rather the desired part. Blanking can be used to cutout parts in almost any 2D shape, but is most commonly used to cut work-pieces with simple geometries that will be further shaped in subsequent processes. Often times multiple sheets are blanked in a single operation. Final parts that are produced using blanking include gears, jewelry, and watch or clock components. Blanked parts typically require secondary finishing smoothing out burrs along the bottom edge.

The blanking process requires a blanking press, sheet metal stock, blanking punch, and blanking die (Fig. 47). The sheet metal stock is placed over the die in the blanking press. The die, instead of having a cavity, has a cutout in the shape of the desired part and must be custom made unless a standard shape is being formed. Above the sheet, resides the blanking punch which is a tool in the shape of the desired part. Both the die and punch are typically made from tool steel or carbide. The hydraulic press drives the punch downward at high speed into the sheet. A small clearance, typically 10-20% of the material thickness, exists between the punch and die. When the punch impacts the sheet, the metal in this clearance quickly bends and then fractures. The blank which has been sheared from the stock now falls freely into the gap in the die. This process is extremely fast, with some blanking presses capable of performing over 1000 strokes per minute.

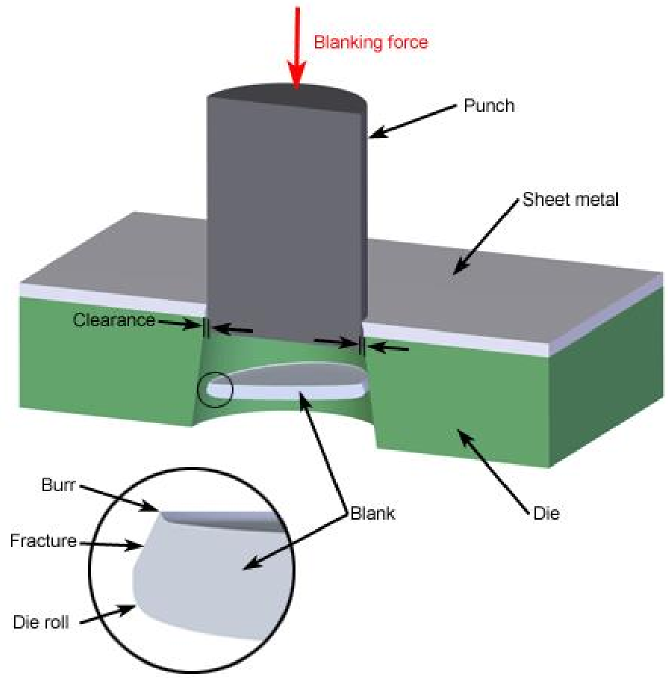


Fig. 47: Blanking process.

- ***Punching***

Punching is very similar to blanking except that the removed material, called the slug, is scrap and leaves behind the desired internal feature in the sheet, such as a hole or slot. Punching can be used to produce holes and cutouts of various shapes and sizes. The most common punched holes are simple geometric shapes (circle, square, rectangle, etc.) or combinations thereof. The edges of these punched features will have some burrs from being sheared but are of fairly good quality. Secondary finishing operations are typically performed to attain smoother edges.

The punching process requires a punch press, sheet metal stock, punch, and dies (Fig. 48). The sheet metal stock is positioned between the punch and die inside the punch press. The die, located underneath the sheet, has a cutout in the shape of the desired feature. Above the sheet, the press holds the punch, which is a tool in the shape of the desired feature. Punches and dies of standard shapes are typically used, but custom tooling can be made for punching complex shapes. This tooling, whether standard or custom, is usually made from tool steel or carbide. The punch press drives the punch downward at high speed through the sheet and into the die below. There is a small clearance between the edge of the punch and the die, causing the material to quickly bend and fracture. The slug that is punched out of the sheet falls freely through the tapered opening in the die.

This process can be performed on a manual punch press, but today computer numerical controlled (CNC) punch presses are most common. A CNC punch press can be hydraulically, pneumatically, or electrically powered and deliver around 600 punches per minute. Also, many CNC punch presses utilize a turret that can hold up to 100 different punches which are rotated into position when needed.

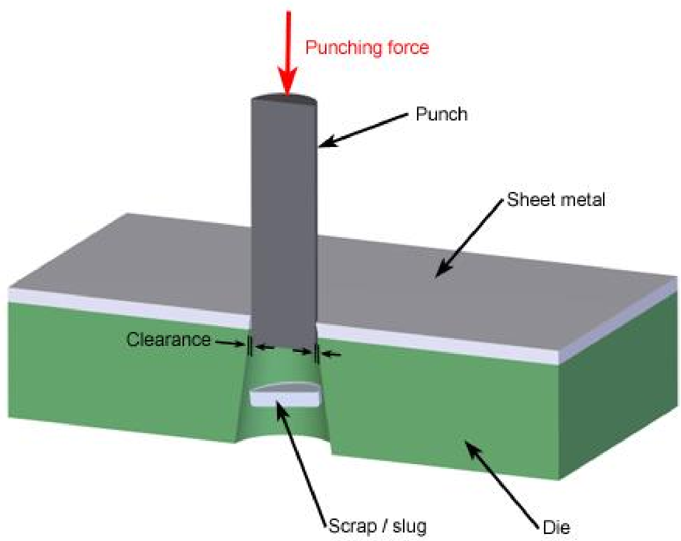


Fig. 48: Punching process

A typical punching operation is one in which a cylindrical punch tool pierces the sheet metal, forming a single hole. However, a variety of operations are possible to form different features. These operations include:

- *Piercing* - The typical punching operation, in which a cylindrical punch pierces a hole into the sheet.
- *Slotting* - A punching operation that forms rectangular holes in the sheet. Sometimes described as piercing despite the different shape.

- *Perforating* - Punching a close arrangement of a large number of holes in a single operation.
- *Notching* - Punching the edge of a sheet, forming a notch in the shape of a portion of the punch.
- *Nibbling* - Punching a series of small overlapping slits or holes along a path to cutout a larger contoured shape. This eliminates the need for a custom punch and die but will require secondary operations to improve the accuracy and finish of the feature.
- *Lancing* - Creating a partial cut in the sheet, so that no material is removed. The material is left attached to be bent and form a shape, such as a tab, vent, or louver.
- *Slitting* - Cutting straight lines in the sheet. No scrap material is produced.
- *Parting* - Separating a part from the remaining sheet, by punching away the material between parts.
- *Cutoff* - Separating a part from the remaining sheet, without producing any scrap. The punch will produce a cut line that may be straight, angled, or curved.
- *Trimming* - Punching away excess material from the perimeter of a part, such as trimming the flange from a drawn cup.
- *Shaving* - Shearing away minimal material from the edges of a feature or part, using a small die clearance. It is used to improve accuracy or finish. Tolerances of ±0.001 inches are possible.
- *Dinking* - A specialized form of piercing used for punching soft metals. A hollow punch, called a dinking die, with beveled, sharpened edges presses the sheet into a block of wood or soft metal.

Some cutting processes use other forces, such thermal energy or abrasion. Common methods of sheet metal cutting that use such forces include: *laser beam cutting, plasma cutting,* and *water jet cutting.*

- ***Laser beam cutting***

Laser cutting uses a high powered laser to cut through sheet metal. A series of mirrors and lenses direct and focus a high-energy beam of light onto the surface of the sheet where it is to be cut. When the beam strikes the surface, the energy of the beam melts and vaporizes the metal underneath. Any remaining molten metal or vapor is blown away from the cut by a stream of gas.

The position of the laser beam relative to the sheet is precisely controlled to allow the laser to follow the desired cutting path.

This process is carried out on laser cutting machines that consist of a power supply, laser system, mirrors, focusing lens, nozzle, pressurized gas, and a work piece table. The laser most commonly used for sheet metal cutting is a CO_2 based laser with approximately 1000-2000 watts of power. However, Nd and Nd-YAG lasers are sometimes used for very high power applications. The laser beam is directed by a series of mirrors and through the "cutting head" which contains a lens and nozzle to focus the beam onto the cutting location (Fig. 49). The beam diameter at the cutting surface is typically around 0.2 mm.

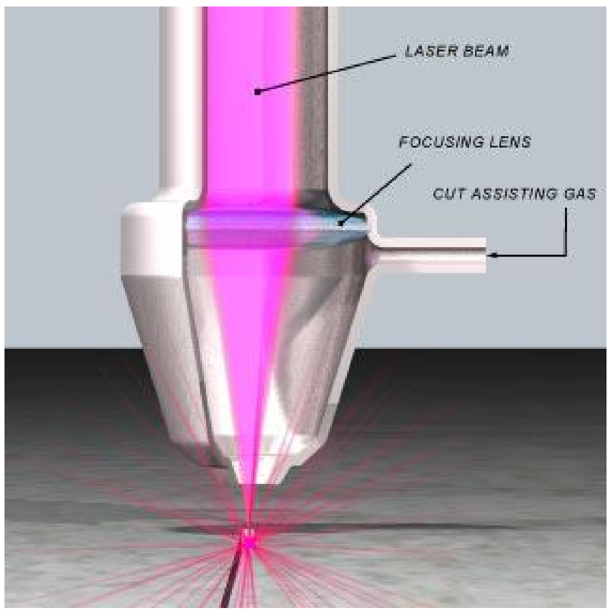


Fig.49: Laser cutting machine

In some machines, the cutting head is able to move in the X-Y plane over the work piece which is clamped to a stationary table below. In other laser cutting machines, the cutting head remains stationary, while the table moves underneath it. Both systems allow the laser beam to cut out any 2D shape in the work piece. As mentioned above, pressurized gas is also used in the process to blow away the molten metal and vapor as the cut is formed. This assist gas, typically oxygen or nitrogen, feeds into the cutting head and is blown out the same nozzle as the laser beam.

Laser cutting can be performed on sheet metals that are both ferrous and non-ferrous. Materials with low reflectivity and conductivity allow the laser beam to be most effective; carbon steel, stainless steel and titanium are most common. Metals that reflect light and conduct heat, such as aluminum and copper alloys, can still be cut but require a higher power laser. Laser cutting can also be used beyond sheet metal applications, to cut plastics, ceramics, stone, wood, etc.

As previously mentioned, laser cutting can be used to cut nearly any 2D shape. However, the most common use is cutting an external profile or complex features. Simple internal features, such as holes or slots are usually punched out using other sheet metal processes. But highly complex shapes and outer part boundaries are well suited for laser cutting.

The fact that laser cutting does not require any physical contact with the material offers many benefits to the quality of the cuts. First, minimal burrs are formed, creating a smooth edge that may not require any finishing. Secondly, no tool contact means only minimal distortion of the sheet will occur. Also, only a small amount of heat distortion is present in the narrow zone affected by the laser beam. Lastly, no contaminates will be embedded into the material during cutting. Although not a quality issue, it is worth noting that the lack of physical tool wear will reduce costs and make laser cutting cost effective for low volume production. Multiple sheets can be cut at once to reduce cost.

- ***Plasma cutting***

Plasma cutting uses a focused stream of ionized gas or plasma, to cut through sheet metal. The plasma flows at extremely high temperatures and high velocity and is directed toward the cutting location by a nozzle. When the plasma contacts the surface below, the metal melts into a molten state. The molten metal is then blown away from the cut by the flow of ionized gas from the nozzle. The position of the plasma stream relative to the sheet is precisely controlled to follow the desired cutting path.

Plasma cutting is performed with a plasma torch (Fig. 50) that may be hand held or, more commonly, computer controlled. CNC (computer numerically controlled) plasma cutting machines enable complex and precision cuts to made. In either type of plasma torch, the flow of plasma is created by first blowing an inert gas at high speed though a nozzle pointed at the cutting surface. An electrical arc, formed through the flow of gas, ionizes the gas into plasma. The nozzle then focuses the flow of plasma onto the cut location. As with laser cutting, this process does not require any physical tooling which reduces initial costs and allows for cost effective low volume production.

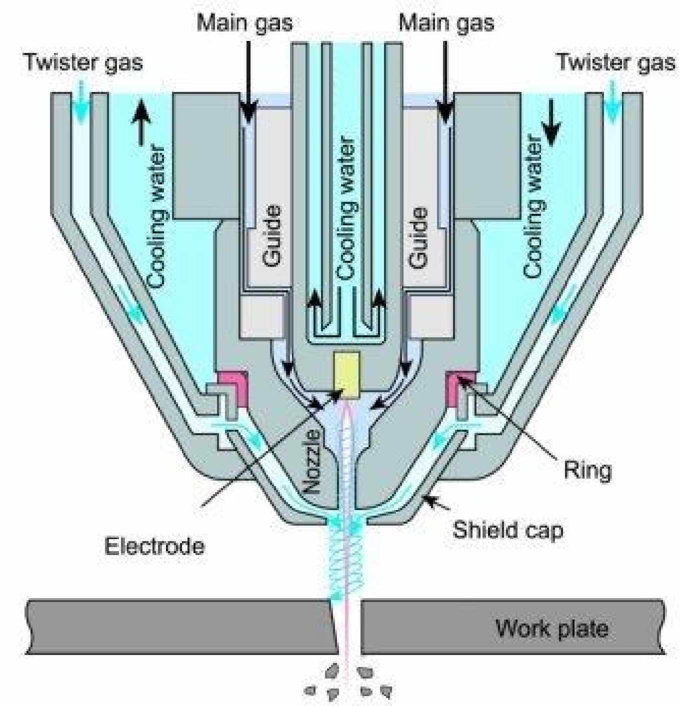


Fig. 50: Plasma torch

The capabilities of plasma cutting vary slightly from laser cutting. While both processes are able to cut nearly any 2D shape out of sheet metal, plasma cutting cannot achieve the same level of precision and finish. Edges may be rough, especially with thicker sheets, and the surface of the material will have an oxide layer that can be removed with secondary processes. However, plasma cutting is capable of cutting through far thicker sheets than laser cutting and is often used for work pieces beyond sheet metal.

- ***Water jet cutting***

Water jet cutting uses a high velocity stream of water to cut through sheet metal (Fig. 51). The water typically contains abrasive particles to wear the material and travels in a narrow jet at high speeds, around 600 m/sec. As a result, the water jet applies very high pressure (around 4000 bars) to the material at the cut location and quickly erodes the material. The position of the water jet is typically computer controlled to follow the desired cutting path.

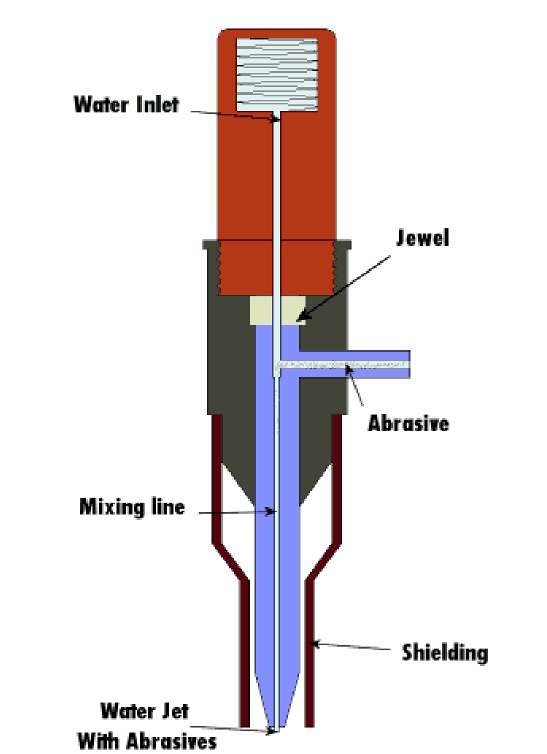


Fig. 51: Water jet cutting head

Water jet cutting can be used to cut nearly any 2D shape out of sheet metal. The width of the cuts is typically between 0.05 and 1.5 mm and the edges are of good quality. Because no burrs are formed, secondary finishing is usually not required. Also, by not using heat to melt the material, like laser and plasma cutting, heat distortion is not a concern.

IV.3.3. Additive Fabrication

Additive fabrication refers to a class of manufacturing processes, in which a part is built by adding layers of material upon one another. These processes are inherently different from subtractive processes or consolidation processes. Subtractive processes, such as milling, turning, or drilling, use carefully planned tool movements to cut away material from a work piece to form the desired part. Consolidation processes, such as casting or molding, use custom designed tooling to solidify material into the desired shape. Additive processes, on the other hand, do not require custom tooling or planned tool movements. Instead, the part is constructed directly from a digital 3-D model created through Computer Aided Design (CAD) software. The 3-D CAD model is converted into many thin layers and the manufacturing equipment uses this geometric data to build each layer sequentially until the part is completed. Due to this approach, additive fabrication is often referred to as layered manufacturing, direct digital manufacturing or solid freeform fabrication.

The most common term for additive fabrication is rapid prototyping. The term "rapid" is used because additive processes are performed much faster than conventional manufacturing processes. The fabrication of a single part may only take a couple hours or can take a few days depending on the part size and the process. However, processes that require custom tooling, such as a mold, to be designed and built may require several weeks. Subtractive processes, such as machining, can offer more comparable production times, but those times can increase substantially for highly complex parts.

The term "prototyping" is used because these additive processes were initially used solely to fabricate prototypes. However, with the improvement of additive technologies, these processes are becoming increasingly capable of high-volume production manufacturing.

Additive fabrication offers several advantages:

- *Speed* - As described above, these "rapid" processes have short build times. Also, because no custom tooling must be developed, the lead time in receiving parts is greatly reduced.

- *Part complexity* - Because no tooling is required, complex surfaces and internal features can be created directly when building the part. Also, the complexity of a part has little effect on build times, as opposed to other manufacturing processes. In molding and casting processes, part complexity may not affect the cycle times, but can require several weeks to be spent on creating the mold. In machining, complex features directly affect the cycle time and may even require more expensive equipment or fixtures.

- *Material types* - Additive fabrication processes are able to produce parts in plastics, metals, ceramics, composites and even paper with properties similar to wood. Furthermore, some processes can build parts from multiple materials and distribute the material based on the location in the part.

- *Low-volume production* - Other more conventional processes are not very cost effective for low-volume productions because of high initial costs due to custom tooling and lengthy setup times. Additive fabrication requires minimal setup and builds a part directly from the CAD model, allowing for low per-part costs for low-volume productions.

With all of these advantages, additive fabrication will still not replace more conventional manufacturing processes for every application. Processes such as machining, molding, and casting are still preferred in specific instances, such as:

- *Large parts* - Additive processes are best suited for relatively small parts because build times are largely dependent upon part size. A larger part in the X-Y plane will require more time to build each layer and a taller part (in the Z direction) will require more layers to be built. This limitation on part size is not shared by some of the more common manufacturing methods. The cycle times in molding and casting processes are typically controlled by the part thickness, and machining times are dependent upon the material and part complexity. Manufacturing large parts with additive processes is also not ideal due to the current high prices of material for these processes.
- *High accuracy and surface finish* - Currently, additive fabrication processes cannot match the precision and finishes offered by machining. As a result, parts produced through additive fabrication may require secondary operations depending on their intended use.
- *High-volume production* - While the production capabilities of additive processes are improving with technology, molding and casting are still preferred for high-volume production. At very large quantities, the per-part cost of tooling is insignificant and the cycle times remain shorter than those for additive fabrication.
- *Material properties* - While additive fabrication can utilize various material types, individual material options are somewhat limited. As a result, materials that offer certain desirable properties may not be available. Also, due to the fabrication methods, the properties of the final part may not meet certain design requirements. Lastly, the current prices for materials used in additive processes are far greater than more commonly used materials for other processes.

Several different additive fabrication processes are commercially available or are currently being developed. Each process may use different materials and different techniques for building the layers of a part. However, each process employs the same basic steps:

- *Create CAD model* - For all additive processes, the designer must first use Computer-Aided Design (CAD) software to create a 3-D model of the part.
- *Convert CAD model into STL model* - Each form of CAD software saves the geometric data representing the 3-D model in different ways. However, the STL format (initially developed for Stereolithography) has become the standard file format for additive processes. Therefore, CAD files must be converted to this file format. The STL format represents the surfaces of the 3-D model as a set of triangles, storing the coordinates for the vertices and normal directions for each triangle.
- *Slice STL model into layers* - Using specialized software, the user prepares the STL file to be built, first designating the location and orientation of the part in the machine. Part orientation impacts several parameters, including build time, part strength, and accuracy. The software then slices the STL model into very thin layers along the X-Y plane. Each layer will be built upon the previous layer, moving upward in the Z direction.
- *Build part one layer at a time* - The machine builds the part from the STL model by sequentially forming layers of material on top of previously formed layers. The technique used to build each layer differs greatly amongst the additive process, as does the material being used. Additive processes can use paper, polymers, powdered metals or metal composites, depending upon the process.
- *Post-processing of part* - After being built, the part and any supports are removed from the machine. If the part was fabricated from a photosensitive material, it must be cured to attain full strength. Minor cleaning and surface finishing, such as sanding, coating or painting, can be performed to improve the part's appearance and durability.

The technologies that can be used to build a part one layer at a time are quite varied and in different stages of development. In order to accommodate different materials, as well as improve build times or part strength, numerous technologies have emerged. Some technologies are commercially available methods of fabricating prototypes, others are quickly becoming viable forms of production manufacturing, and newer technologies are continuously being developed. These different methods of additive fabrication can be classified by the type of material that is employed:

- *Liquid-based processes* - These additive technologies typically use photocurable polymer resins and cure selected portions of the resin to form each part layer. The most common liquid-based additive process is *Stereolithography (SLA)*, which was the first commercially available additive process. Parts produced using this technology offer high accuracy and an appearance similar to molded parts. However, photocurable polymers offer somewhat poor mechanical properties which may worsen over time. Other liquid-based processes include *Jetted Photopolymer* and *Ink Jet Printing,* which may use a single jet or multiple jets.

- *Powder-based processes* - In powder-based processes, such as *Selective Laser Sintering (SLS)*, a selected portion of powdered material is melted or sintered to form each part layer. The use of powdered material enables parts to be fabricated using polymers, metals or ceramics. Also, the mechanical properties of these parts are better and more stable than a photocured polymer part. Other powder-based processes include *Direct Metal Laser Sintering (DMLS)* and *Three Dimensional Printing (3DP)*.

- *Solid-based processes* - Solid-based processes use a variety of solid, non-powder, materials and each process differs in how it builds the layers of a part. Most solid-based processes use sheet-stacking methods, in which very thin sheets of material are layered on top of one another and the shape of the layer is cut out. The most common sheet-stacking process is *Laminated Object Manufacturing (LOM)*, which uses thin sheets of paper, but other processes make use of polymer or metal sheets. Other solid-based processes use solid strands of polymer, not sheets, such as *Fused Deposition Modeling (FDM)* which extrudes and deposits the polymer into layers.

- ***Stereolithography (SLA)***

SLA is the most widely used rapid prototyping technology. It can produce highly accurate and detailed polymer parts. It was the first rapid prototyping process, introduced in 1988 by 3D Systems, Inc., based on work by inventor Charles Hull. It uses a low-power, highly focused UV laser to trace out successive cross-sections of a three-dimensional object in a vat of liquid photosensitive polymer. As the laser traces the layer, the polymer solidifies and the excess areas are left as liquid. When a layer is completed, a leveling blade is moved across the surface to smooth it before depositing the next layer. The platform is lowered by a distance equal to the layer thickness (typically 0.05 ï 0.075 mm), and a subsequent layer is formed on top of the previously completed layers. This process of tracing and smoothing is repeated until the build is complete. Once complete, the part is elevated above the vat and drained. Excess polymer is swabbed or rinsed away from the surfaces. In many cases, a final cure is given by placing the part in a UV oven. After the final cure, supports are cut off the part and surfaces are polished, sanded or otherwise finished.

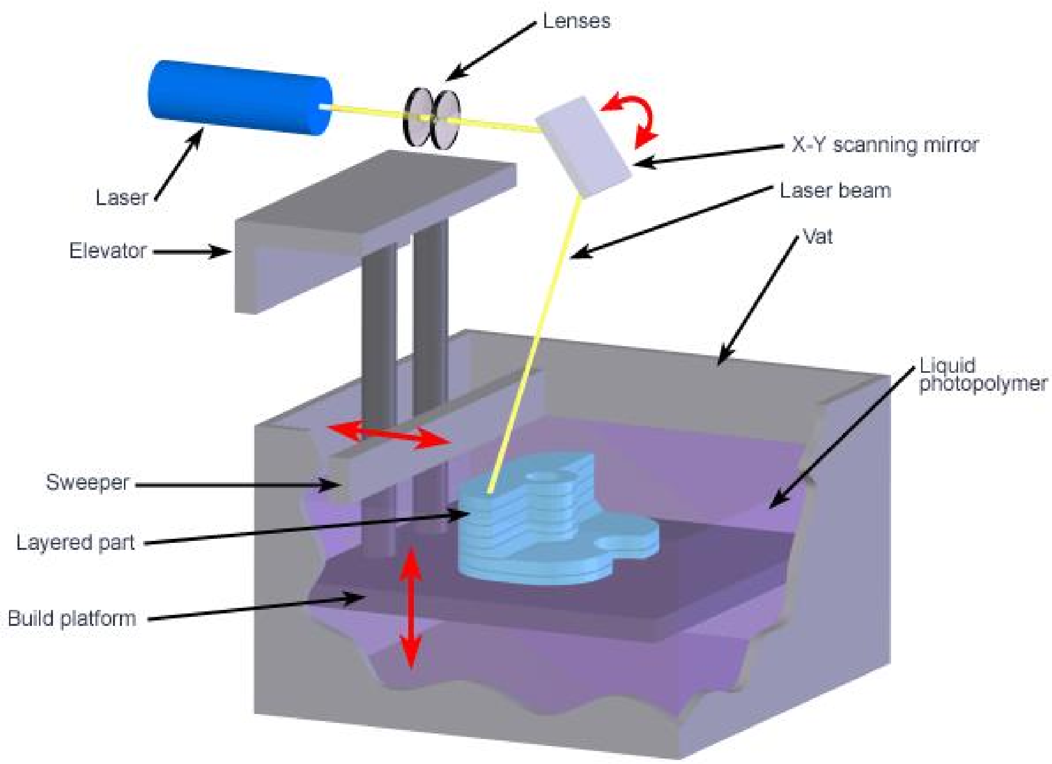


Fig. 52: Stereolithography (SLA)

- ***Fused Deposition Modeling (FDM)***

FDM was developed by Stratasys in Eden Prairie, Minnesota. In this process, a plastic or wax material is extruded through a nozzle that traces the parts cross sectional geometry layer by layer. The build material is usually supplied in filament form, but some setups utilize plastic pellets fed from a hopper instead. The nozzle contains resistive heaters that keep the plastic at a temperature just above its melting point so that it flows easily through the nozzle and forms the layer. The plastic hardens immediately after flowing from the nozzle and bonds to the layer below. Once a layer is built, the platform lowers, and the extrusion nozzle deposits another layer. The layer thickness and vertical dimensional accuracy is determined by the extruder die diameter, which ranges from 0.125 ï 0.35 mm. In the X-Y plane, 0.025 mm resolution is achievable. A range of materials are available including ABS, polyamide, polycarbonate, polyethylene, polypropylene, and investment casting wax.

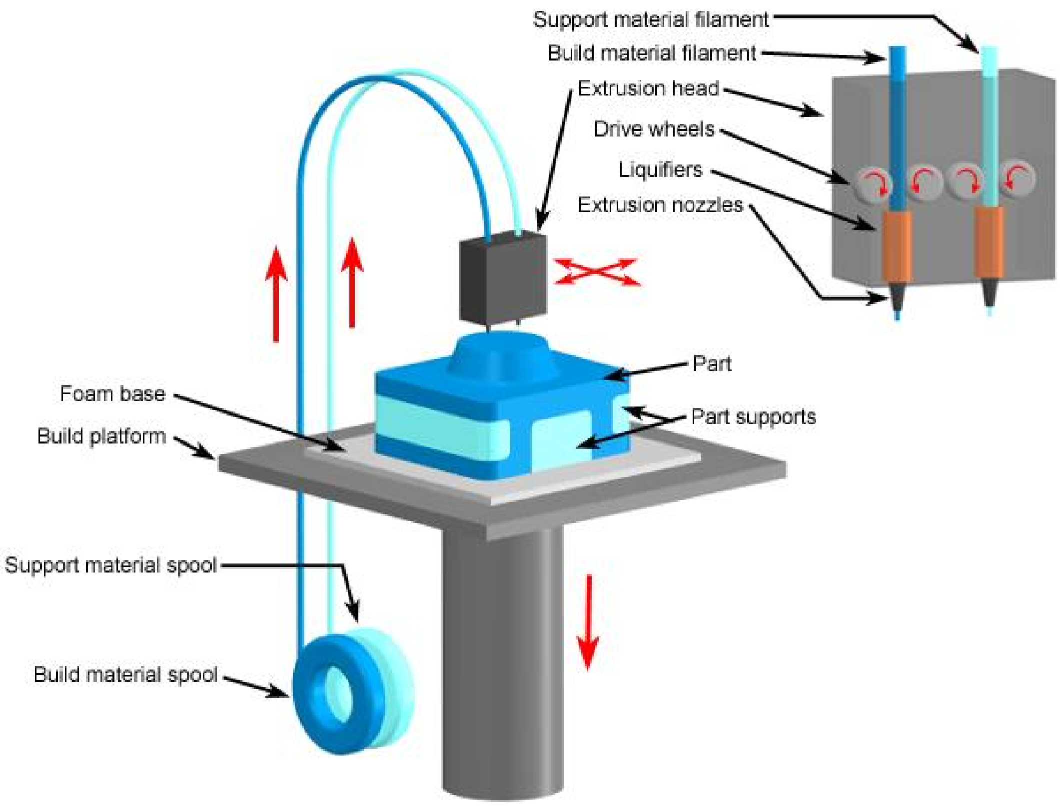


Fig. 53: Fused Deposition Modeling (FDM)

- ***Selective Laser Sintering (SLS)***

SLS was developed at the University of Texas in Austin, by Carl Deckard and colleagues. The technology was patented in 1989 and was originally sold by DTM Corporation. DTM was acquired by 3D Systems in 2001. The basic concept of SLS is similar to that of SLA. It uses a moving laser beam to trace and selectively sinter powdered polymer and/or metal composite materials into successive cross-sections of a three-dimensional part. As in all rapid prototyping processes, the parts are built upon a platform that adjusts in height equal to the thickness of the layer being built. Additional powder is deposited on top of each solidified layer and sintered. This powder is rolled onto the platform from a bin before building the layer. The powder is maintained at an elevated temperature so that it fuses easily upon exposure to the laser. Unlike SLA, special support structures are not required because the excess powder in each layer acts as a support to the part being built. With the metal composite material, the SLS process solidifies a polymer binder material around steel powder (100 micron diameter) one slice at a time, forming the part. The part is then placed in a furnace, at temperatures in excess of 900 °C, where the polymer binder is burned off and the part is infiltrated with bronze to improve its density. The burn-off and infiltration procedures typically take about one day, after which secondary machining and finishing is performed. Recent improvements in accuracy and resolution, and reduction in stair-stepping, have minimized the need for secondary machining and finishing. SLS allows for a wide range of materials, including nylon, glass-filled nylon, SOMOS (rubber-like), Truform (investment casting), and the previously discussed metal composite.

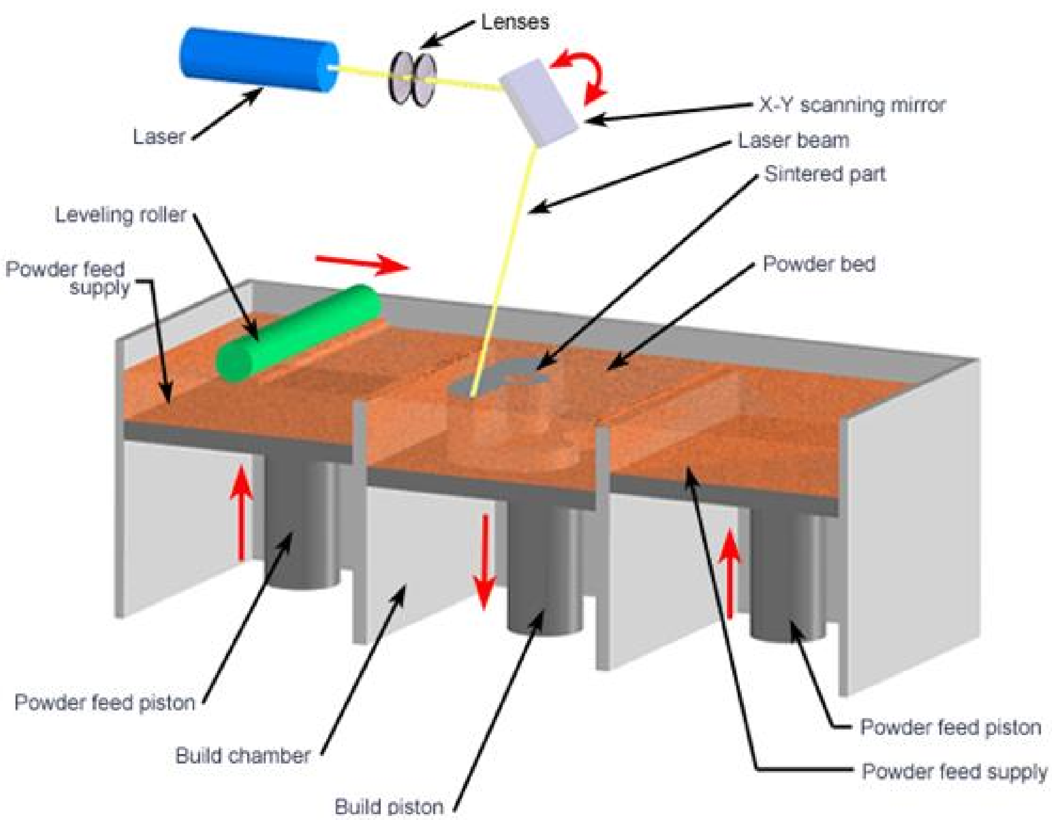


Fig. 54: Selective Laser Sintering (SLS)

- ***Direct Metal Laser Sintering (DMLS)***

DMLS was developed jointly by Rapid Product Innovations (RPI) and EOS GmbH, starting in 1994, as the first commercial rapid prototyping method to produce metal parts in a single process. With DMLS, metal powder (20 micron diameter), free of binder or fluxing agent, is completely melted by the scanning of a high power laser beam to build the part with properties of the original material. Eliminating the polymer binder avoids the burn-off and infiltration steps, and produces a 95% dense steel part compared to roughly 70% density with Selective Laser Sintering (SLS). An additional benefit of the DMLS process compared to SLS is higher detail resolution due to the use of thinner layers, enabled by a smaller powder diameter. This capability allows for more intricate part shapes. Material options that are currently offered include alloy steel, stainless steel, tool steel, aluminum, bronze, cobalt-chrome, and titanium. In addition to functional prototypes, DMLS is often used to produce rapid tooling, medical implants, and aerospace parts for high heat applications.

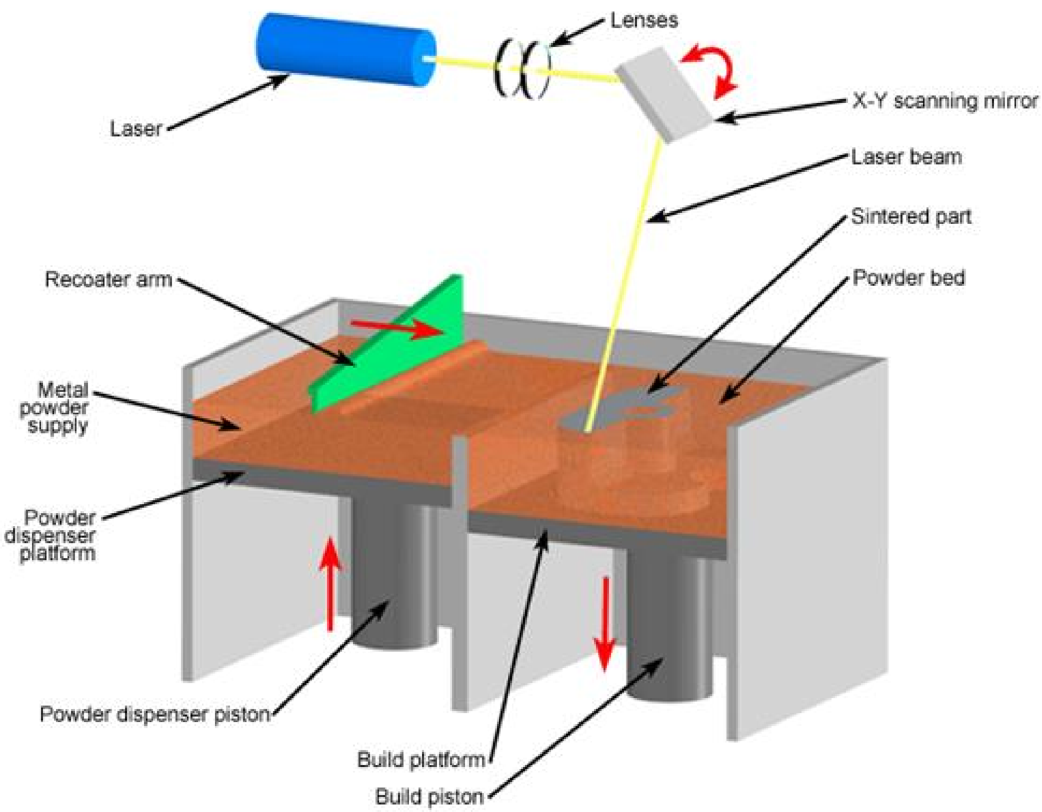


Fig. 55: Direct Metal Laser Sintering (DMLS)

The DMLS process can be performed by two different methods, powder deposition and powder bed, which differ in the way each layer of powder is applied. In the powder deposition method, the metal powder is contained in a hopper that melts the powder and deposits a thin layer onto the build platform. In the powder bed method (shown below), the powder dispenser piston raises the powder supply and then a recoater arm distributes a layer of powder onto the powder bed. A laser then sinters the layer of powder metal. In both methods, after a layer is built the build piston lowers the build platform and the next layer of powder is applied. The powder deposition method offers the advantage of using more than one material, each in its own hopper. The powder bed method is limited to only one material but offers faster build speeds.

- ***Three Dimensional Printing (3DP)***

3DP technology was developed at the Massachusetts Institute of Technology and licensed to several corporations. The process is similar to the Selective Laser Sintering (SLS) process, but instead of using a laser to sinter the material, an ink-jet printing head deposits a liquid adhesive that binds the material. Material options, which include metal or ceramic powders, are somewhat limited but are inexpensive relative to other additive processes. 3D Printing offers the advantage of fast build speeds, typically 2-4 layers per minute. However, the accuracy, surface finish, and part strength are not quite as good as some other additive processes. 3D Printing is typically used for the rapid prototyping of conceptual models (limited functional testing is possible).

The 3D printing process begins with the powder supply being raised by a piston and a leveling roller distributing a thin layer of powder to the top of the build chamber. A multi-channel ink-jet print head then deposits a liquid adhesive to targeted regions of the powder bed. These regions of powder are bonded together by the adhesive and form one layer of the part. The remaining free standing powder supports the part during the build. After a layer is built, the build platform is lowered and a new layer of powder added, leveled, and the printing repeated. After the part is completed, the loose supporting powder can be brushed away and the part removed. 3D printed parts are typically infiltrated with a sealant to improve strength and surface finish.

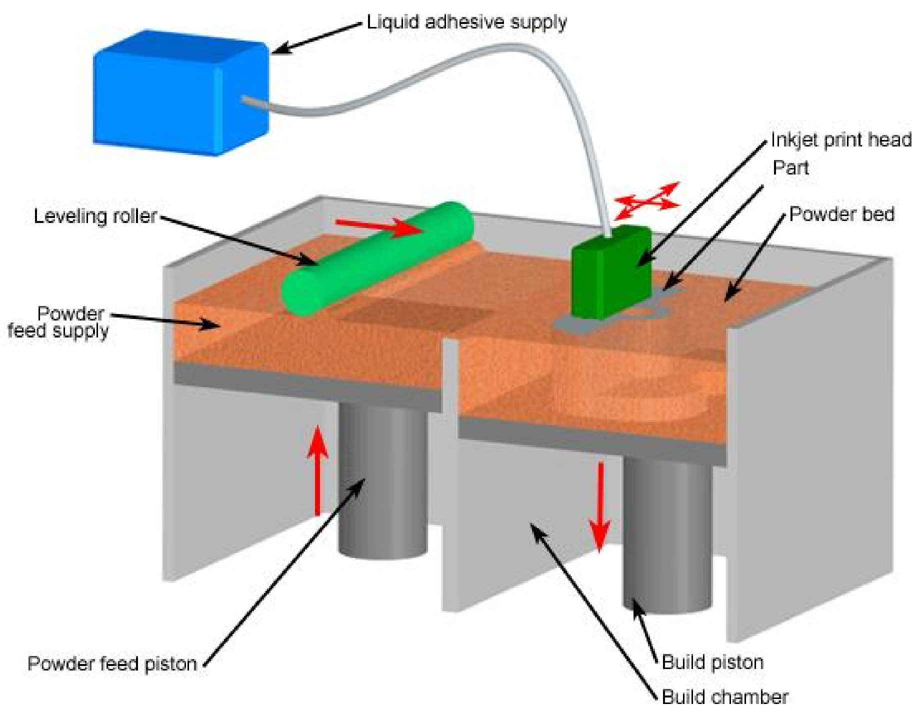


Fig. 56: Three Dimensional Printing (3DP)

- ***Inkjet Printing***

The additive fabrication technique of inkjet printing is based on the 2D printer technique of using a jet to deposit tiny drops of ink onto paper. In the additive process, the ink is replaced with thermoplastic and wax materials, which are held in a melted state. When printed, liquid drops of these materials instantly cool and solidify to form a layer of the part. For this reason, the process if often referred to as thermal phase change inkjet printing. Inkjet printing offers the advantages of excellent accuracy and surface finishes. However, the limitations include slow build speeds, few material options, and fragile parts. As a result, the most common application of inkjet printing is prototypes used for form and fit testing. Other applications include jewelry, medical devices, and high-precisions products. Several manufactures have developed different inkjet printing devices that use the basic technique described above. Inkjet printers from Solidscape Inc., such as the ModelMaker (MM), use a single jet for the build material and another jet for support material. 3D Systems has implemented their MultiJet Moldeling (MJM) technology into their ThermoJet Modeler machines that utilize several hundred nozzles to enable faster build times.

The inkjet printing process, as implemented by Solidscape Inc., begins with the build material (thermoplastic) and support material (wax) being held in a melted state inside two heated reservoirs. These materials are each fed to an inkjet print head which moves in the X-Y plane and shoots tiny droplets to the required locations to form one layer of the part. Both the build material and support material instantly cool and solidify. After a layer has been completed, a milling head moves across the layer to smooth the surface. The particles resulting from this cutting operation are vacuumed away by the particle collector. The elevator then lowers the build platform and part so that the next layer can be built. After this process is repeated for each layer and the part is complete, the part can be removed and the wax support material can be melted away.

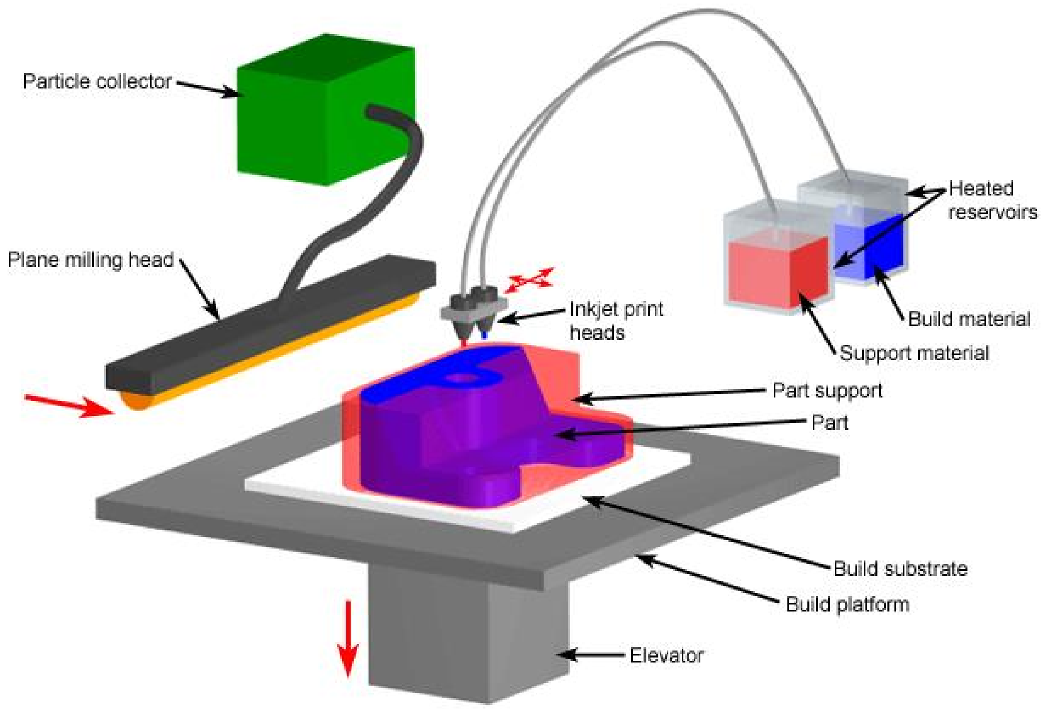


Fig. 57: Inkjet Printing

- ***Jetted Photopolymer***

Jetted photopolymer is an additive process that combines the techniques used in Inkjet Printing and Stereolithography. The method of building each layer is similar to Inkjet Printing, in that it uses an array of inkjet print heads to deposit tiny drops of build material and support material to form each layer of a part. However, as in Stereolithography, the build material is a liquid acrylatebased photopolymer that is cured by a UV lamp after each layer is deposited. For this reason, Jetted Photopolymer is sometimes referred to as Photopolymer Inkjet Printing. The advantages of this process are very good accuracy and surface finishes. However, the feature detail and material properties are not quite as good as Stereolithography. As with Inkjet Printing, the most common application of this technology is prototypes used for form and fit testing. Other applications include rapid tooling patterns, jewelry, and medical devices.

Two companies that have developed jetted photopolymer devices include Objet Geometries Ltd. and 3D Systems. The equipment designed by both companies deposits the photopolymer build material as described above, but differs in the application of support material. Objet, an Israeli company, commercialized their PolyJet technology in 2000. In the PolyJet system, the support material is also a photopolymer that is deposited from a second print head and cured by the UV lamp. This support material does not cure the same as the build material and can later be washed away with pressurized water. 3D systems commercialized their InVision systems in 2003. These jetted photopolymer devices use a separate print head to deposit a wax support material. After the part is completed, the wax is melted away.

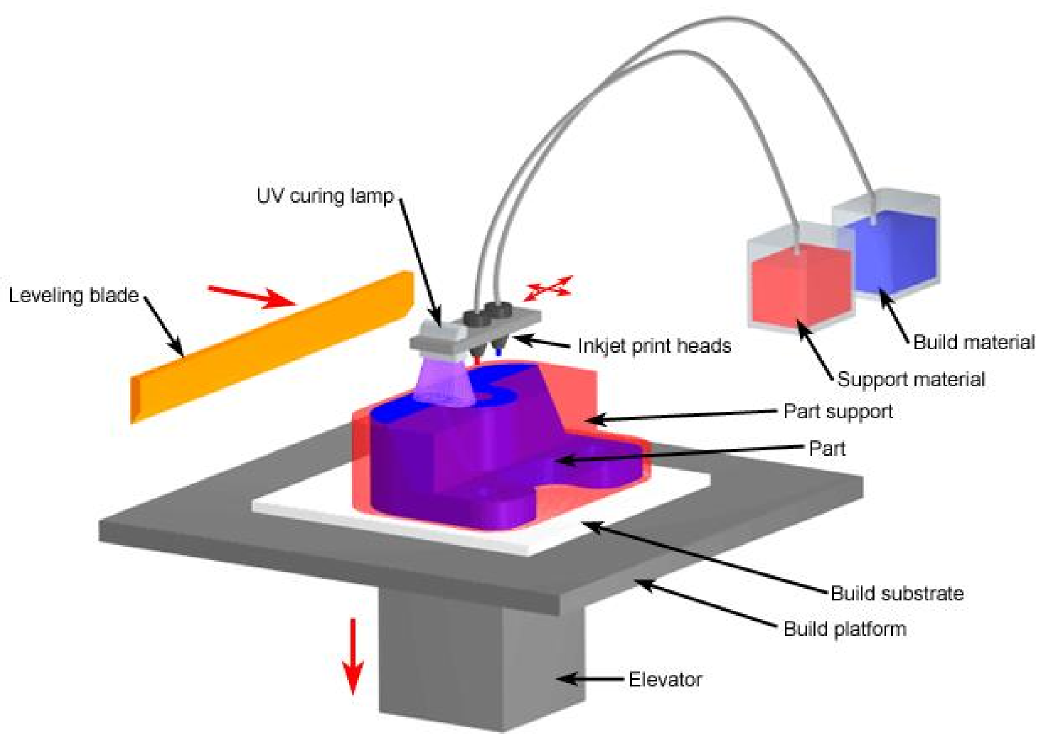


Fig. 58: Jetted photopolymer

- ***Laminated Object Manufacturing (LOM)***

The first commercial Laminated Object Manufacturing (LOM) system was shipped in 1991. LOM was developed by Helisys of Torrance, CA. The main components of the system are a feed mechanism that advances a sheet over a build platform, a heated roller to apply pressure to bond the sheet to the layer below, and a laser to cut the outline of the part in each sheet layer. Parts are produced by stacking, bonding, and cutting layers of adhesive-coated sheet material on top of the previous one. A laser cuts the outline of the part into each layer. After each cut is completed, the platform lowers by a depth equal to the sheet thickness (typically 0.002-0.020 in), and another sheet is advanced on top of the previously deposited layers. The platform then rises slightly and the heated roller applies pressure to bond the new layer. The laser cuts the outline and the process is repeated until the part is completed. After a layer is cut, the extra material remains in place to support the part during build.

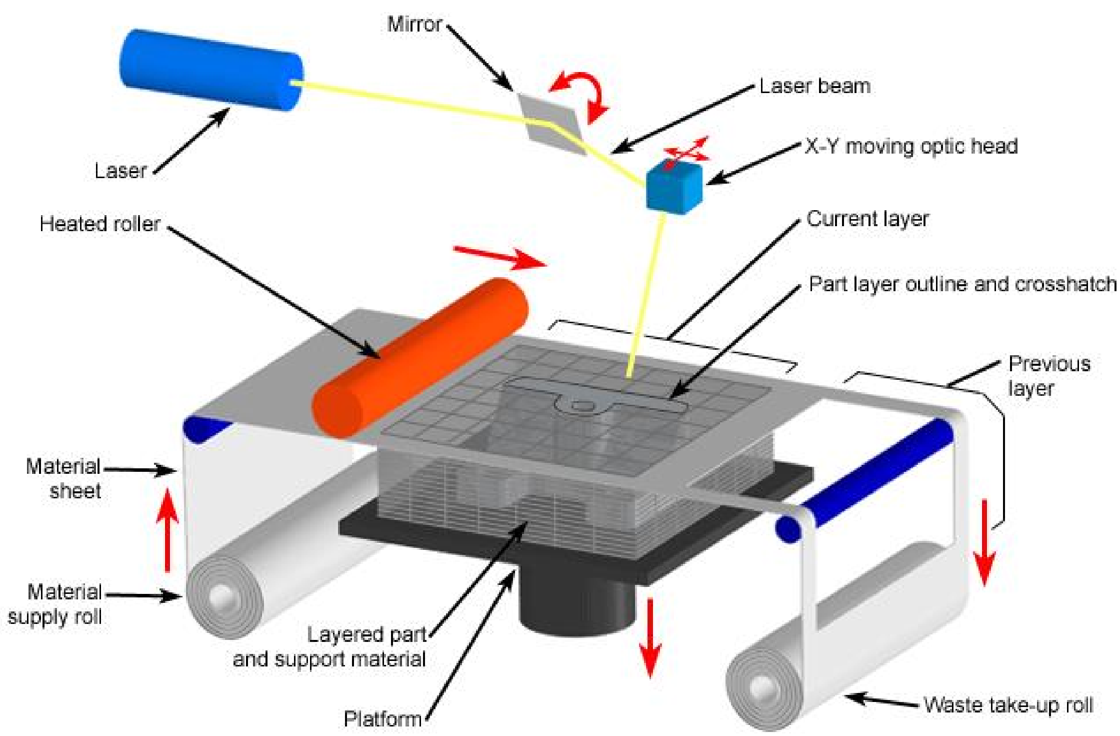


Fig. 59: Laminated Object Manufacturing (LOM)

Additive fabrication processes initially yielded parts with few applications due to limited material options and mechanical properties. However, improvements to the processing technologies and material options have expanded the possibilities for these layered parts. Now, additive fabrication is used in a variety of industries, including the aerospace, architectural, automotive, consumer product, medical product, and military industries. The application of parts in these industries is quite vast. For example, some parts are merely aesthetic such as jewelry, sculptures, or 3D architectural models. Others are customized to meet the user's personal needs such as specially fitted sports equipment, dental implants, or prosthetic devices. The following three categories are often used to describe the different application of additive fabrication and may be applied to all of the above industries:

- *Rapid prototyping* - Prototypes for visualization, form/fit testing, and functional testing
- *Rapid tooling* - Molds and dies fabricated using additive processes
- *Rapid manufacturing* - Medium-to-high volume production runs of end-use parts

Chapter V: *Assembly*

The assembly of parts and subassemblies to form a product of desired functionality may involve a number of joining operations, such as mechanical fastening, adhesive bonding, and welding. Although assembly processes are not value-adding operations and are commonly seen as necessary but óówastefulôô tasks, most of todayôs products cannot be manufactured as single entities. Thus while some products are passed on to customers as a collection of individual parts for their assembly by the user, with an incentive of reduced price, most products have to be assembled prior to their sale because of either their complex and long assembly process or the specialized tools needed for their joining that are not usually owned by the perspective customers.

Since an assembly process may add significant cost to the fabrication of a product, different manufacturing strategies have been adopted over the past century for increased assembly efficiency. These cost-cutting measures have included the use of mass production techniques for reduced setup time and costs, as well as specialization of human operators on one or two specific joining tasks; the use of automation for highly repetitive operations; and more recently the use of modular product design for simplification of assembly.

Assembly relies on the interchangeability of parts concept. Individual partsô dimensions must be carefully controlled, within their tolerance levels, so that they can be assembled without further rework during their joining. This is a paramount issue in the batch production of goods (i.e., more than one of a kind) and even more important when in the future individual components that wear out must be replaced with off-the-shelf parts. Systems operating at remote locations requiring replacement parts cannot be expected to be returned to a service location for custom fitting of broken or worn parts.

The objective of this chapter is to address a variety of representative methods for different types of joining operations available to a manufacturer in the fabrication of multicomponent products. These include mechanical fastening, adhesive bonding, welding, brazing and soldering.

V.1. Mechanical Fastening

Joining mechanical components through fasteners (screws, bolts, rivets, etc.) is most desirable when future disassembly of the product is expected for maintenance, or when other joining techniques, such as welding or adhesive joining are not feasible.

Several factors affect the number, type and locations of fasteners used in assembling two or more parts: strength of the joints (tensile or compression), ease of disassembly and appearance.

The location and number of fasteners to be used in a mechanical joint is primarily a function of the strength level we wish to achieve, subject to geometrical constraints (e.g., minimum wall thickness, distance from edge, and potential creation of stress concentrations). The strength of such joints can normally be calculated analytically (for example, through the area of contact of the number of threads on a fastener). Though, in some cases, empirical methods may have to be employed for more reliable estimations.

Product appearance also influences the locations of the fasteners and their types. However, we must be very conscious of ease of assembly and disassembly when making such placement decisions. Designers and manufacturing engineers must not place fasteners at hard-to-reach places simply for aesthetic purposes, especially if the product is to be assembled by the customer, who may not have a large variety of tools at his or her disposal for fastening.

- ***Bolted joints***

Bolted joints are one of the most common elements in construction and machine design. They consist of fasteners that capture and join other parts, and are secured with the mating of screw threads.

There are two main types of bolted joint designs: tension joints and shear joints (Fig. 60). In the tension joint, the bolt and clamped components of the joint are designed to transfer the external tension load through the joint by way of the clamped components through the design of a proper balance of joint and bolt stiffness. The joint should be designed such that the clamp load is never overcome by the external tension forces acting to separate the joint (and therefore the joined parts see no relative motion).

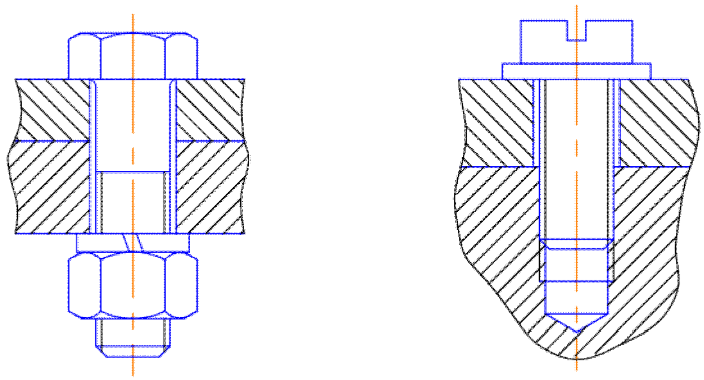


Fig. 60: Bolted joint designs

The second type of bolted joint transfers the applied load in shear on the bolt shank and relies on the shear strength of the bolt. Tension loads on such a joint are only incidental. A preload is still applied but is not as critical as in the case where loads are transmitted through the joint in tension.

Other such shear joints do not employ a preload on the bolt as they allow rotation of the joint about the bolt, but use other methods of maintaining bolt/joint integrity. This may include clevis linkages, joints that can move, and joints that rely on a locking mechanism (like lock washers, thread adhesives, and lock nuts).

In both the tension and shear joint design cases, some level of tension preload in the bolt and resulting compression preload in the clamped components is essential to the joint integrity. The preload target can be achieved by applying a measured torque to the bolt, measuring bolt extension, heating to expand the bolt then turning the nut down, torque the bolt to the yield point, testing ultrasonically or by a certain number of degrees of relative rotation of the threaded components. Each method has a range of uncertainties associated with it, some of which are very substantial.

- ***Rivets***

A rivet is a permanent mechanical fastener (Fig. 61). Before being installed, a rivet consists of a smooth cylindrical shaft with a head on one end. The end opposite the head is called the buck-tail. On installation the rivet is placed in a punched or drilled hole, and the tail is upset, or bucked (i.e., deformed), so that it expands to about 1.5 times the original shaft diameter, holding the rivet in place. To distinguish between the two ends of the rivet, the original head is called the factory head and the deformed end is called the shop head or buck-tail.

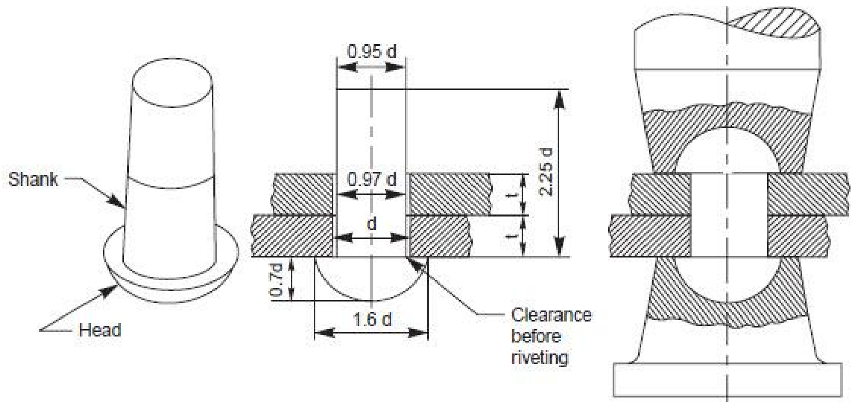


Fig. 61: Rivet

Because there is effectively a head on each end of an installed rivet, it can support tension loads (loads parallel to the axis of the shaft); however, it is much more capable of supporting shear loads (loads perpendicular to the axis of the shaft). Bolts and screws are better suited for tension applications.

- ***Snap joints***

Snap joints are a very simple, economical and rapid way of joining two different components.

All types of snap joints have in common the principle that a protruding part of one component, e.g., a hook, stud or bead is deflected briefly during the joining operation and catches in a depression (undercut) in the mating component. After the joining operation, the snap-fit features should return to a stress-free condition.

The joint may be separable or inseparable depending on the shape of the undercut; the force required to separate the components varies greatly according to the design. It is particularly important to bear the following factors in mind when designing snap joints:

- mechanical load during the assembly operation,
- force required for assembly.

A wide range of design possibilities exists for snap joints. In view of their high level of flexibility, plastics are usually very suitable materials for this joining technique.

In the following, the many design possibilities have been reduced to a few basic shapes (Fig. 62).

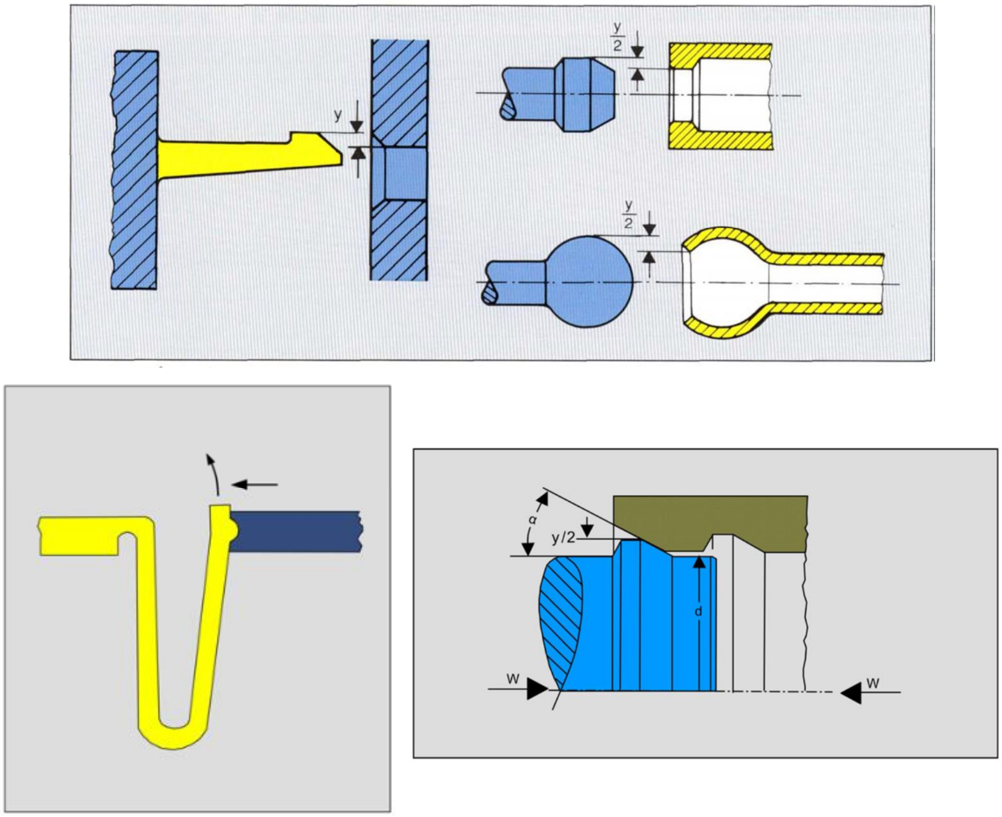


Fig. 62: Snap joints

The most important are:

- cantilever snap joints,
- U-shaped snap joints,
- torsion snap joints,
- annular snap joints

V.2. Adhesive Bonding

Adhesives can be utilized for the joining of most engineering materials: metals, plastics, ceramics, wood, and paper. The joining process involves the placement of an adhesive filler material between the surfaces of two segments of a product (adherents) and the subsequent curing of the adhesives using an initiating mechanism: applications of heat and mixing of two or more reactive components. Some adhesives employ a solvent that evaporates or is absorbed by the adherents that are joined and leaves behind a dry hardened adhesive layer.

The resultant joint is permanent and frequently cannot be broken without damage to one or both parts.

The first use of adhesives in manufacturing was in the bonding of load-bearing aircraft components during the ó40s. Since then, they have been used in the machine-tool industry, the automotive industry, the electronics industry, the medical industry and the household products industry.

Some advantages of adhesive bonding are:

- *Joining of dissimilar materials*: Different materials or similar materials with different thermal characteristics (e.g., thermal-expansion coefficient) can be adhesive bonded.
- *Good damping characteristics*: Adhesive bonded assemblies yield good resistance to mechanical vibration, where the adhesive acts as a vibration damper, as well as resistance to fatigue.
- *Uniform stress distribution:* Broader joining areas yield better stress distribution, allowing the use of thinner assembly components and resulting in significant weight reductions.
- *Thermal and electrical insulation:* Adhesives provide electric and thermal insulation, as well as resistance to corrosion.
- *Niche application:* Adhesive bonding can be used in the joining of parts with complex shapes and different thicknesses that do not allow the use of other joining processes. It can also be used to yield visually attractive products with no visible joints or fasteners.

Naturally, as do other processes, adhesive bonding suffers from numerous drawbacks: partsô surfaces must be carefully prepared to avoid contamination; the joints can be damaged in the face of impact forces and weakened significantly at high temperatures and actual bonding strength may not be accurately verifiable.

V.2.1. Joint Design and Surface Preparation

The first step in joint design for adhesive bonding is to understand how adhesives behave under mechanical loading. Tensile loads that may induce peeling or cleavage must be avoided owing to low cohesive strength of adhesives. In contrast, adhesive joints can resist high shear and compression loads, when the joint overlap area is sufficiently large to allow distribution of the applied load. However, high pure shear forces applied for long periods of time may eventually damage the joint.

Empirical data have shown that there is an upper limit to the degree of overlapping of the joints for increased load carrying. Beyond a certain limit, one cannot increase the strength of a joint simply by increasing the length of the overlap. In reference to joint thickness, although engineering intuition would advocate the minimization of bond thickness, several studies have shown that some level of increase may actually strengthen the joints.

Most adhesive bonding joints are of the lap-joint type and its variants, some of which are shown in Fig. 63. The simple lap joint requires a toughened adhesive that will not experience a brittle failure due to distortions occurring under shear loading. Otherwise, the geometry of the joint or its configuration, through the addition of third-party segments, must be varied for optimal distribution of loads.

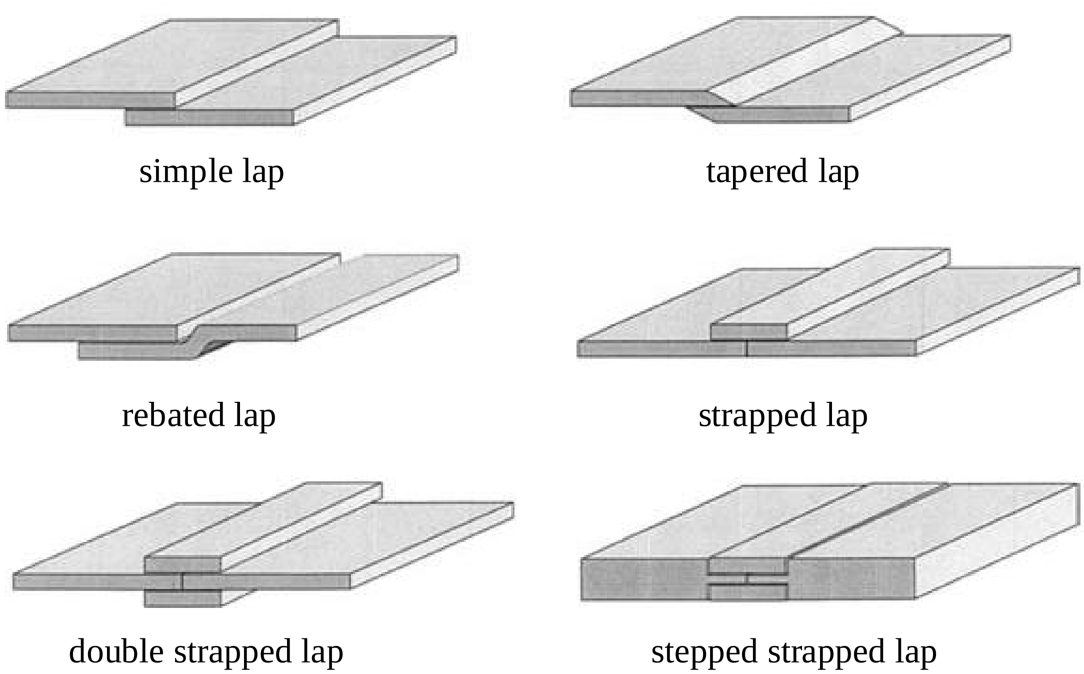
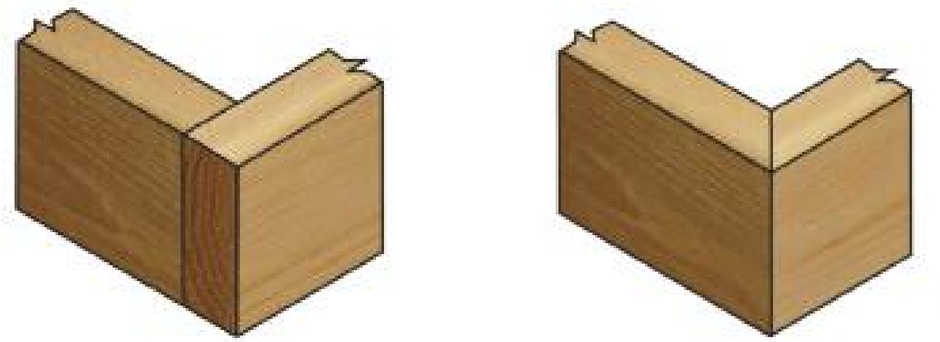


Fig. 63: Lap adhesive bonding joints

Butt joints (end-to-end contact) are normally viewed as poor forms of adhesive bonding, unless large contact areas are created. Most communes used are illustrated in Fig. 64.



simple butt joint mitter joint

Fig. 64: Butt joints

Surface preparation is the most important step in adhesive bonding. Contaminants present on the adherents poorly affect wetting and cause premature failure of the joint.

There are three common techniques for surface cleaning:

- solvent degreasing through wiping or vapor degreasing,
- chemical etching or anodizing,
- the use of surface primers.

Naturally, the optimal technique(s) selected for surface preparation is a function of the materials of the adherents. However, all surface preparation activities, regardless of adherentsô materials, must be quickly followed by the deposition of the adhesive and subsequent bonding operation.

V.2.2. Adhesives and Bonding Techniques

Adhesives can be broadly classified into two groups: organic and inorganic. The former can be further classified into natural (e.g., dextrin, rubber) and synthetic (e.g., acrylic, epoxy, phenolic) types. Next, several organic synthetic adhesives will be briefly reviewed.

- ***Epoxy adhesives***

These adhesives normally have two parts: the epoxy resin and its hardener. They are commonly used on large aluminum objects. Single-part, temperature-hardened epoxy adhesives can also be found in use in the manufacturing industry.

- ***Acrylic adhesives***

This class contains a variety of subspecies: anaerobic, cyanoacrylate, and toughened acrylics. Anaerobic adhesives are one-part, solventless pastes, which cure at room temperature in the absence of oxygen. The bond is brittle. Cyanoacrylate adhesives are also one-part adhesives that cure at room temperature. Toughened acrylic adhesives are two-part, quick-setting adhesives that cure at room temperature after the mixing of the resin and the initiator. Overall, acrylic adhesives have a wide range of applications: metals in cars and aircraft, fiberglass panels in boats, electronic components on printed circuit boards, etc.

- ***Hot-melt adhesives***

These (thermoplastic) single-part materials include polymers such as polyethylene, polyester, and polyamides. They are applied as (molten) liquid adhesives and allowed to cure under (accelerated) cooling conditions. Owing to their modest strengths, they are not widely used for load-carrying applications.

The methods of applying adhesives onto prepared surfaces vary from industry to industry and are based on the type of adhesive materials:

- manual brushing or rolling (similar to painting),
- silk screening (placement of a metal screen on designated surfaces and deposition through cutouts on the screen),
- direct deposition or spraying using robot-operated pressure guns,
- slot coating (deposition through a slot onto a moving substrate.

V.2.3. Industrial Applications

Industrial examples of adhesive bonding include:

- *Automotive industry*: Sealants and adhesives are widely used in the manufacturing of automobiles in temporary or permanent roles. On the welding line, examples include front hoods and trunk lids, hemming parts of door bottoms, front and rear fenders, and roof rails. On the trim line, examples include door trims, windshields, windows, wheel housings, and weather strips. Other automotive examples include (neoprene and nitrile rubber) phenolic adhesives used in the bonding of brake linings to withstand intermittent high shear loads at high temperatures, drain holes on body panels, and of course carpet fixing.

- *Machine-tool industry*: Retaining adhesives have been utilized by machine-tool builders for strengthening a variety of bushings and bearings that are press-fitted against loosening due to intense vibrations (e.g., in chucks with hydraulic clamping mechanisms and in the spindle). Adhesives are also commonly used on a variety of body panels.

- *Other industries*: Epoxy phenolics have been used in (aluminum to aluminum) bonding of honeycomb aircraft and missile parts onto their respective skins, in solar cells in satellites, and even in resinï glass laminates in appliances. One- or two-part epoxy adhesives have also been used in joining cabinet, telephone booth, and light fixture parts. Other examples include small electric armatures, solar heating panels, skis, tennis rackets, golf clubs, beverage containers, medical skin pads, loudspeakers, shoes and glassware.

V.3. Welding

Welding is a fabrication or sculptural process that joins materials, usually metals or thermoplastics, by causing coalescence. This is often done by melting the work pieces and adding a filler material to form a pool of molten material (the weld pool) that cools to become a strong joint, with pressure sometimes used in conjunction with heat, or by itself, to produce the weld. This is in contrast with soldering and brazing, which involve melting a lower-melting-point material between the work pieces to form a bond between them, without melting the work pieces.

Some of the best known welding methods include:

- ***Shielded metal arc welding (SMAW) -*** also known as "stick welding", it uses an electrode that has flux, the protectant for the puddle, around it. The electrode holder holds the electrode as it slowly melts away. Slag protects the weld puddle from atmospheric contamination.
- ***Gas tungsten arc welding (GTAW) -*** also known as TIG (tungsten, inert gas), uses a non-consumable tungsten electrode to produce the weld. The weld area is protected from atmospheric contamination by an inert shielding gas such as Argon or Helium.

- ***Gas metal arc welding (GMAW)*** **-** commonly termed MIG (metal, inert gas), uses a wire feeding gun that feeds wire at an adjustable speed and flows an argon-based shielding gas or a mix of argon and carbon dioxide (CO_2) over the weld puddle to protect it from atmospheric contamination.
- ***Flux-cored arc welding (FCAW)*** **-** almost identical to MIG welding except it uses a special tubular wire filled with flux; it can be used with or without shielding gas, depending on the filler.
- ***Submerged arc welding (SAW)*** **-** uses an automatically fed consumable electrode and a blanket of granular fusible flux. The molten weld and the arc zone are protected from atmospheric contamination by being "submerged" under the flux blanket.
- ***Electroslag welding (ESW)*** **-** a highly productive, single pass welding process for thicker materials between 1 inch (25 mm) and 12 inches (300 mm) in a vertical or close to vertical position.

Many different energy sources can be used for welding, including a gas flame, an electric arc, a laser, an electron beam, friction, and ultrasound. While often an industrial process, welding may be performed in many different environments, including in open air, under water, and in outer space.

Welding is a hazardous undertaking and precautions are required to avoid burns, electric shock, vision damage, inhalation of poisonous gases and fumes, and exposure to intense ultraviolet radiation.

V.3.1. Shielded Metal Arc Welding (SMAW)

Shielded metal arc welding (SMAW), also known as manual metal arc welding (MMA or MMAW), flux shielded arc welding or informally as stick welding, is a manual arc welding process that uses a consumable electrode coated in flux to lay the weld (Fig. 65). An electric current, in the form of either alternating current or direct current from a welding power supply, is used to form an electric arc between the electrode and the metals to be joined. The work piece and the electrode melt forming the weld pool that cools to form a strong joint. As the weld is laid, the flux coating of the electrode disintegrates, giving off vapors that serve as a shielding gas and providing a layer of slag, both of which protect the weld area from atmospheric contamination.

Because of the versatility of the process and the simplicity of its equipment and operation, shielded metal arc welding is one of the world's most popular welding processes. It dominates other welding processes in the maintenance and repair industry, and though flux-cored arc welding is growing in popularity, SMAW continues to be used extensively in the construction of steel structures and in industrial fabrication. The process is used primarily to weld iron and steels (including stainless steel) but aluminum, nickel and copper alloys can also be welded with this method.

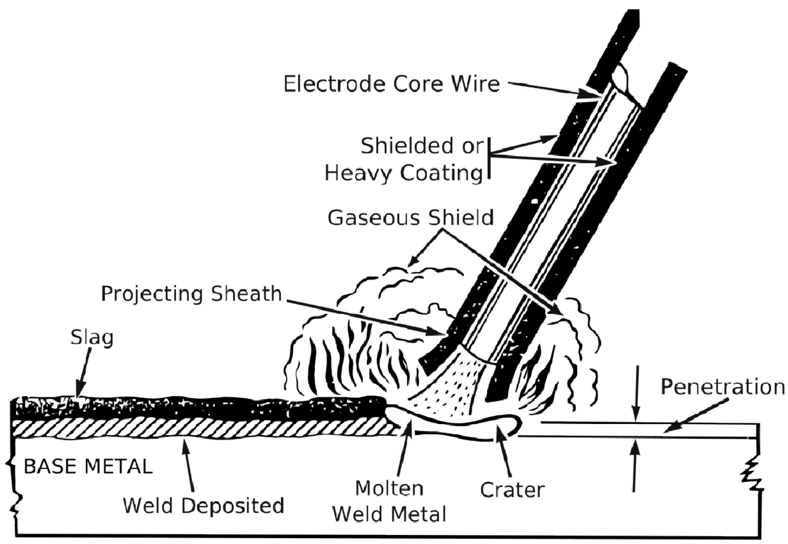


Fig. 65: Shielded metal arc welding (SMAW)

To strike the electric arc, the electrode is brought into contact with the work piece by a very light touch with the electrode to the base metal then is pulled back slightly. This initiates the arc and thus the melting of the work piece and the consumable electrode, and causes droplets of the electrode to be passed from the electrode to the weld pool. As welding progresses and the electrode melts, the welder must periodically stop welding to remove the remaining electrode stub and insert a new electrode into the electrode holder. This activity, combined with chipping away the slag, reduces the amount of time that the welder can spend laying the weld, making SMAW one of the least efficient welding processes. In general, the operator factor, or the percentage of operator's time spent laying weld, is approximately 25%.

The actual welding technique utilized depends on the electrode, the composition of the work piece, and the position of the joint being welded. The choice of electrode and welding position also determine the welding speed. Flat welds require the least operator skill, and can be done with electrodes that melt quickly but solidify slowly. This permits higher welding speeds. Sloped, vertical or upside-down welding requires more operator skill, and often necessitates the use of an electrode that solidifies quickly to prevent the molten metal from flowing out of the weld pool. However, this generally means that the electrode melts less quickly, thus increasing the time required to lay the weld.

V.3.2. Gas Tungsten Arc Welding (GTAW)

Gas tungsten arc welding (GTAW), also known as tungsten inert gas (TIG) welding, is an arc welding process that uses a non-consumable tungsten electrode to produce the weld (Fig. 66). The weld area is protected from atmospheric contamination by an inert shielding gas (argon or helium), and a filler metal is normally used, though some welds, known as autogenous welds, do not require it. A constant-current welding power supply produces electrical energy, which is conducted across the arc through a column of highly ionized gas and metal vapors known as plasma.

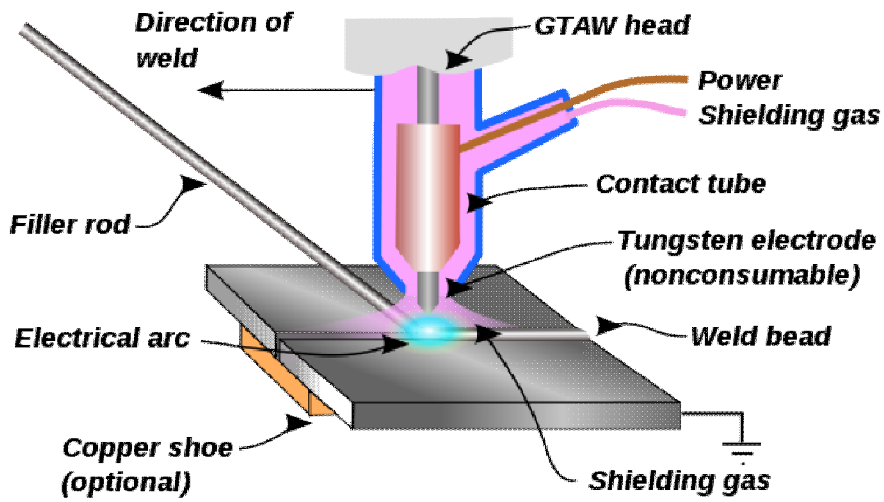


Fig. 66: Gas tungsten arc welding (GTAW)

GTAW is most commonly used to weld thin sections of stainless steel and non-ferrous metals such as aluminum, magnesium, and copper alloys. The process grants the operator greater control over the weld than competing processes such as shielded metal arc welding and gas metal arc welding, allowing for stronger, higher quality welds. However, GTAW is comparatively more complex and difficult to master, and furthermore, it is significantly slower than most other welding techniques. A related process, plasma arc welding, uses a slightly different welding torch to create a more focused welding arc and as a result is often automated.

Manual gas tungsten arc welding is often considered the most difficult of all the welding processes commonly used in industry. Because the welder must maintain a short arc length, great care and skill are required to prevent contact between the electrode and the work piece.

To strike the welding arc, a high frequency generator (similar to a Tesla coil) provides an electric spark. This spark is a conductive path for the welding current through the shielding gas and allows the arc to be initiated while the electrode and the work piece are separated, typically about 1.5÷3 mm apart. The electric arc produced can reach temperatures of at least 5000 °C.

This high voltage, high frequency burst can be damaging to some vehicle electrical systems and electronics, because induced voltages on vehicle wiring can also cause small conductive sparks in the vehicle wiring or within semiconductor packaging. Vehicle 12V power may conduct across these ionized paths, driven by the high-current 12V vehicle battery. These currents can be sufficiently destructive as to disable the vehicle; thus the warning to disconnect the vehicle battery power from both +12 and ground before using welding equipment on vehicles.

Welders often develop a technique of rapidly alternating between moving the torch forward (to advance the weld pool) and adding filler metal. The filler rod is withdrawn from the weld pool each time the electrode advances, but it is never removed from the gas shield to prevent oxidation of its surface and contamination of the weld. Filler rods composed of metals with low melting temperature, such as aluminum, require that the operator maintain some distance from the arc while staying inside the gas shield. If held too close to the arc, the filler rod can melt before it makes contact with the weld puddle. As the weld nears completion, the arc current is often gradually reduced to allow the weld crater to solidify and prevent the formation of crater cracks at the end of the weld.

V.3.3. Gas Metal Arc Welding (GMAW)

Gas metal arc welding (GMAW), sometimes referred to by its subtypes metal inert gas (MIG) welding or metal active gas (MAG) welding, is a welding process in which an electric arc forms between a consumable wire electrode and the work piece metal(s), which heats the work piece metal(s), causing them to melt and join (Fig. 67). Along with the wire electrode, a shielding gas feeds through the welding gun, which shields the process from contaminants in the air.

The process can be semi-automatic or automatic. A constant voltage, direct current power source is most commonly used with GMAW, but constant current systems, as well as alternating current can be used. There are four primary methods of metal transfer in GMAW, called globular, short-circuiting, spray and pulsed-spray, each of which has distinct properties and corresponding advantages and limitations.

For most of its applications gas metal arc welding is a fairly simple welding process to learn requiring no more than a week or two to master basic welding technique. Even when welding is performed by well-trained operators weld quality can fluctuate since it depends on a number of external factors. All GMAW is dangerous, though perhaps less so than some other welding methods, such as shielded metal arc welding.

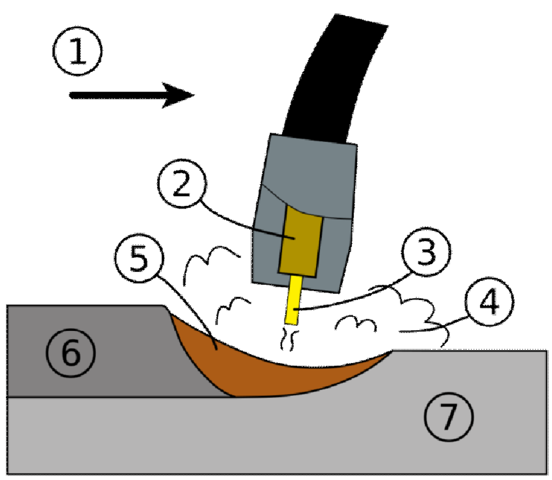


Fig. 67: GMAW weld area. (1) Direction of travel, (2) Contact tube, (3) Electrode, (4) Shielding gas, (5) Molten weld metal, (6) Solidified weld metal, (7) Work piece.

GMAW is one of the most popular welding methods, especially in industrial environments. It is used extensively by the sheet metal industry and, by extension, the automobile industry. There, the method is often used for arc spot welding, thereby replacing riveting or resistance spot welding. It is also popular for automated welding, in which robots handle the work pieces and the welding gun to speed up the manufacturing process.

V.3.4. Flux-cored arc welding (FCAW)

Flux-cored arc welding (FCAW or FCA) is a semi-automatic or automatic arc welding process. FCAW requires a continuously-fed consumable tubular electrode containing a flux and a constant-voltage or, less commonly, a constant-current welding power supply (Fig. 68). An externally supplied shielding gas is sometimes used, but often the flux itself is relied upon to generate the necessary protection from the atmosphere, producing both gaseous protection and liquid slag protecting the weld. The process is widely used in construction because of its high welding speed and portability.

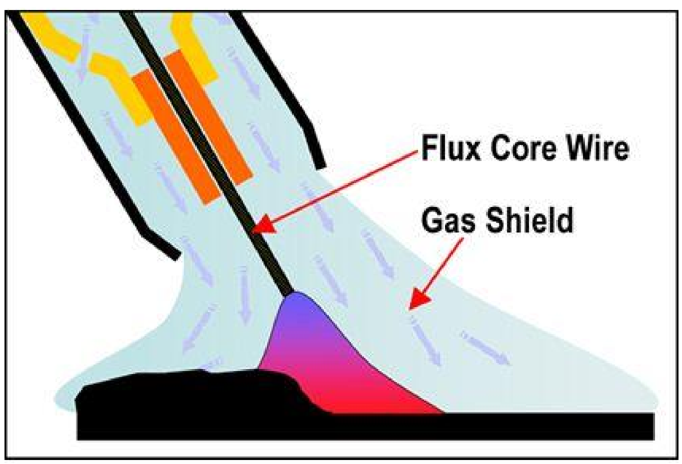


Fig. 68: Flux-cored arc welding (FCAW or FCA)

One type of FCAW requires no shielding gas. This is made possible by the flux core in the tubular consumable electrode. However, this core contains more than just flux; it also contains various ingredients that when exposed to the high temperatures of welding generate a shielding gas for protecting the arc. This type of FCAW is attractive because it is portable and generally has good penetration into the base metal. Also, windy conditions need not be considered.

Some disadvantages are that this process can produce excessive, noxious smoke (making it difficult to see the weld pool); as with all welding processes, the proper electrode must be chosen to obtain the required mechanical properties. Operator skill is a major factor as improper electrode manipulation machine setup can cause porosity.

Another type of FCAW uses a shielding gas that must be supplied by an external supply. This is known informally as "dual shield" welding. This type of FCAW was developed primarily for welding structural steels. In fact, since it uses both a flux-cored electrode and an external shielding gas, one might say that it is a combination of gas metal (GMAW) and flux-cored arc welding (FCAW). This particular style of FCAW is preferable for welding thicker and out-of-position metals. The slag created by the flux is also easy to remove. The main advantages of this process is that in a closed shop environment, it generally produces welds of better and more consistent mechanical properties, with fewer weld defects than either the SMAW or GMAW processes. In practice it also allows a higher production rate, since the operator does not need to stop periodically to fetch a new electrode, as is the case in SMAW. However, like GMAW, it cannot be used in a windy environment as the loss of the shielding gas from air flow will produce porosity in the weld.

V.3.5. Submerged Arc Welding (SAW)

Submerged arc welding (SAW) is a common arc welding process. The first patent on the submerged-arc welding (SAW) process was taken out in 1935 and covered an electric arc beneath a bed of granulated flux. Originally developed and patented by Jones, Kennedy and Rothermund, the process requires a continuously fed consumable solid or tubular (metal cored) electrode (Fig. 69). The molten weld and the arc zone are protected from atmospheric contamination by being "submerged" under a blanket of granular fusible flux consisting of lime, silica, manganese oxide, calcium fluoride, and other compounds. When molten, the flux becomes conductive, and provides a current path between the electrode and the work. This thick layer of flux completely covers the molten metal thus preventing spatter and sparks as well as suppressing the intense ultraviolet radiation and fumes that are a part of the shielded metal arc welding (SMAW) process.

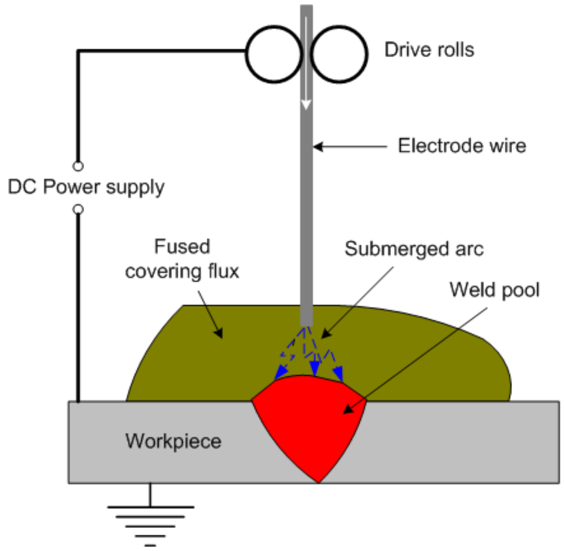


Fig. 69: Submerged arc welding (SAW)

SAW is normally operated in the automatic or mechanized mode, however, semi-automatic (hand-held) SAW guns with pressurized or gravity flux feed delivery are available. The process is normally limited to the flat or horizontal-fillet welding positions (although horizontal groove position welds have been done with a special arrangement to support the flux). Deposition rates approaching 45 kg/h have been reported - this compares to ~5 kg/h (max) for shielded metal arc welding. Although currents ranging from 300 to 2000 A are commonly utilized; currents of up to 5000 A have also been used (multiple arcs).

Single or multiple (2 to 5) electrode wire variations of the process exist. SAW strip-cladding utilizes a flat strip electrode (e.g. 60 mm wide x 0.5 mm thick). DC or AC power can be used, and combinations of DC and AC are common on multiple electrode systems. Constant voltage welding power supplies are most commonly used; however, constant current systems in combination with a voltage sensing wire-feeder are available.

V.3.6. Electroslag Welding (ESW)

Electroslag welding (ESW) is a highly productive, single pass welding process for thick (greater than 25 mm up to about 300 mm) materials in a vertical or close to vertical position. (ESW) is similar to electrogas welding, but the main difference is the arc starts in a different location. An electric arc is initially struck by wire that is fed into the desired weld location and then flux is added (Fig. 70). Additional flux is added until the molten slag, reaching the tip of the electrode, extinguishes the arc. The wire is then continually fed through a consumable guide tube (can oscillate if desired) into the surfaces of the metal work pieces and the filler metal are then melted using the electrical resistance of the molten slag to cause coalescence. The wire and tube then move up along the work piece while a copper retaining shoe that was put into place before starting (can be water-cooled if desired) is used to keep the weld between the plates that are being welded.

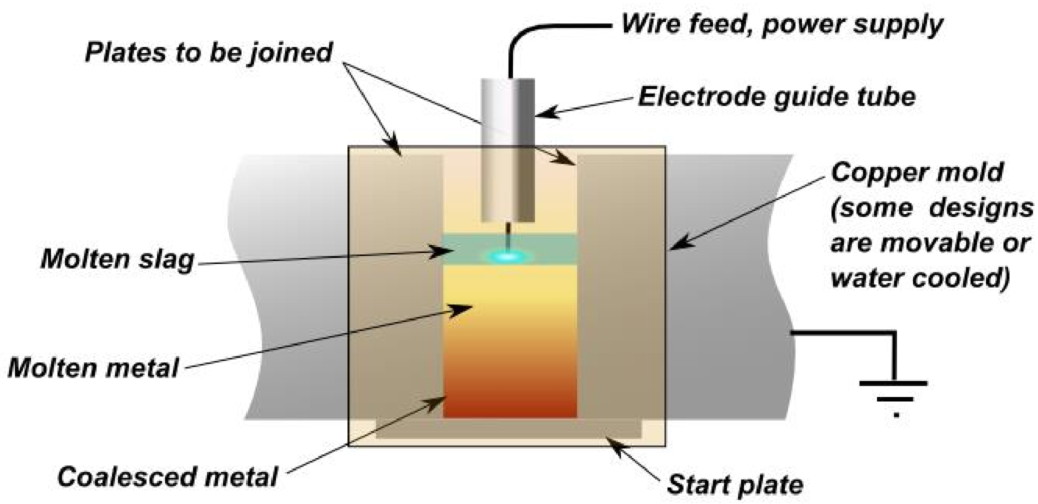


Fig. 70: Electroslag welding (ESW)

Electroslag welding is used mainly to join low carbon steel plates and/or sections that are very thick. It can also be used on structural steel if certain precautions are observed. This process uses a direct current (DC) voltage usually ranging from about 600 A and 40÷50 V, higher currents are needed for thicker materials. Because the arc is extinguished, this is not an arc process.

V.3.7. Weldability and Design for Welding

Most engineering materials (metals, plastics, and ceramics) can be welded; some with more difficulty than others, using one of the available welding techniques. Due to the melting and solidification cycle and the resultant microstructure changes, one must carefully monitor all the welding process parameters, including shielding gases, fluxes, welding current and voltage, welding speed and orientation, and preheating and cooling rates.

In terms of different materials: carbon and low-carbon alloy steels are weldable with no significant difficulties; thicknesses of up to 15 mm are more easily weldable than thicker work pieces that require preheating (to slow down the cooling rate); aluminum and copper alloys are difficult to weld because of their high thermal conductivity and high thermal expansion; titanium and tantalum alloys are weldable with careful shielding of the weld region; thermoplastics (such as polyvinychloride, polyethylene, and polypropylene) are weldable at low temperatures (300 to 400 ºC), though glass-reinforced plastics are not generally weldable; ceramics (SiO_2 - AlO_2) have also been welded in the past using CO_2 and Nd.

Welding defects can be classified as external (visible) and internal defects. Some of these are listed below:

- ***Misalignment***: It is an external defect caused by poor preparation.
- ***Distortion:*** It is an external defect caused by residual stresses due to unsuitable process parameters.
- ***Incomplete penetration:*** It is an internal defect caused by excessive weld speed, low weld current, too small a gap, or poor preparation.
- ***Undercut:*** It is an internal defect - a groove that appears at the edge of the joint, caused by high current or voltage, irregular wire speed, or too high welding speed.
- ***Porosity:*** It is an internal defect - in the form of isolated or grouped bubbles, caused by an insufficient flow of gas, moist or rusty base metals, or entrapment of gases.
- ***Cracking:*** It is an internal defect - localized fine breaks that may occur while the joint is hot or cold, caused by hydrogen embrittlement, internal stress, lack of penetration, excessive sulphur and phosphorus content in base metal, or rapid cooling.

In addition to the process parameters that must be controlled to avoid welding defects, a designer may consider the following additional guidelines: weld locations should be chosen to maximize strength and avoid stress concentrations, though some awareness of intended use and appearance is important; careful edge preparation must be employed if unavoidable; and welding should be minimized owing to potential dimensional distortions.

V.4. Brazing and Soldering

Brazing and soldering are similar joining processes: a filler metal is melted and deposited into a gap between segments of a product. Unlike in welding, the base materials (similar or different) are not melted as part of the joining process.

In brazing, the filler material normally has a melting point above 450 ºC, but certainly lower than that of the base materials, whereas, in soldering, the filler materials have melting points well below 450 ºC.

Capillary forces play an important role in both processes in the wetting of the joint surfaces by the molten (fluid-state) filler material and thus the flow of the liquid metal into the gaps between the two base segments.

The use of low-melting-point metals in joining operations has been around for the past 3000 years. The primary advantages of such processes have been joining of dissimilar materials joining of thinned walled and/or complex geometry parts that may be affected by high temperatures (such as those in welding), achievement of strong bonds (stronger than adhesive bonding but weaker than welding), and adaptability to mass production and automation.

V.4.1. Brazing

Brazing is a simple joining process, in which a liquid metal flows into narrow gaps between two parts and solidifies to form a strong, permanent bond. Ferrous and nonferrous filler metals normally have melting temperatures above 450 ºC, but below those of the two base materials, which do not melt during the joining process. Almost all metals, and some ceramic alloys, can be brazed using filler metals, such as aluminum and silicon, copper and its alloys, gold and silver and their alloys, and magnesium and nickel alloys.

The ability of the liquid filler metal to wet the materials it is attempting to join, and completely to flow into the desired gaps prior to its solidification, determines the success or failure of a brazing application.

Besides surface tension, the following parameters affect the brazing process: temperature and duration of melting, surface preparation, joint design and gap dimensions, source and rate of heating, and, naturally, base material and filler metal characteristics.

The brazing of all metals and ceramics depends on the wetting of the filler material at relatively high temperatures. Formation of unwanted oxides at such high temperatures, however, may impede the ability of the filler material to wet the joint surfaces. Use of a suitable flux complemented with an inert gas atmosphere dissolves and/or prevents the formation of oxides and promotes wetting by lowering the surface tension of the filler metal. Common fluxes used for brazing include chlorides, fluorides, borates, and alkalis.

Filler materials commonly used in brazing are:

- Aluminumï silicon: This group of alloys can be used as fillers for aluminum (and its alloys) base materials at melting temperatures of 500 ÷ 600 ºC, heat exchangers, aircraft parts, car radiators, etc.
- Copper and copper-zinc: This group of alloys can be used as fillers for ferrous-base materials at melting temperatures of 750 to 1700 ºC.
- Nickel and nickel alloys: This group of alloys can be used as fillers for stainless steel, nickel, and cobalt-based alloys at melting temperatures of 950 to 1200 ºC.
- Silver-copper: This group of alloys can be used as fillers for titanium, ceramics, steel, and nickel at melting temperatures of 620 to 850 ºC honeycomb structures, tubing, etc.

- ***Brazing Methods***

Manual torch brazing is the simplest and most commonly used technique, primarily reserved for one-of-a-kind (repair or prototyping) jobs.

Other brazing techniques that allow automation for batch or continuous processing include:

Furnace brazing: Parts with preplaced filler segments are brazed in (electric, gas, or oil-heated) furnaces that typically employ a conveyor for (time-controlled) continuous through motion of the parts to be joined.

Induction and resistance brazing: Electrical resistance is utilized to melt preplaced filler materials quickly.

Dip brazing: Complete immersion of small parts into a (constant temperature) molten filler material vat provides wetting and filling of the joints.

In the past three decades, the brazing process has been successfully automated and applied in numerous industries:

- Cemented carbides onto cutting toolsômetal shanks.
- Ceramic (automotive) bladed-turbocharger hubs onto metal shafts.
- Ceramic-on-metal joining in microelectronic products.
- Metal-on-metal (automotive) pipes.

V.4.2. Soldering

Soldering is a joining process in which two segments of a product are bonded using a liquid filler material (solder) that rapidly solidifies after deposition.

As in brazing, the process occurs at the melting temperature of the solder (typically, below 315 ºC), which is significantly below the melting temperature of the base material. Wetting of the joint surfaces by the liquid solder and its flow into the desired gaps of optimal clearances due to capillary forces is a paramount issue in soldering. Due to wetting and bonding of the joints at low temperatures, soldering is a desirable joining process for applications with no significant load carrying situations, such as soldering of electronic components on printed circuit boards (PCBs).

Joint design guidelines for soldering are very similar to those established for brazing. Of the two most common joint configurations, butt and lap joints, the lap joint are the preferred one because of its strength (Fig. 71).

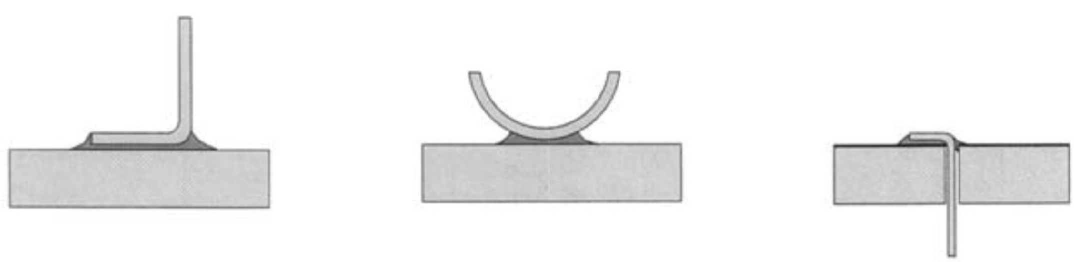


Fig. 71: Soldering joint configurations

Since joint strength is directly related to overlap area, designers must carefully configure lap joints for achieving uniform solder flow into the gaps. A common solution to such flow problems, however, is the pre-placement of the solder prior to heating. Pre-placement can be achieved using solid pre-forms of solders, such as washers, wire rings, discs, or powder form solder suspended in a paste.

The soldering process starts with a careful preparation of the surface - removal of contaminants and degreasing. An appropriate soldering flux is then applied to prevent oxidization and facilitate wetting. Inorganic fluxes include hydrochloric and hydrofluoric acids and zinc chloride and ammonium chloride salts. Organic fluxes include lactic and oleic acids, aniline hydrochloride halogens, and a variety of resins. Fluxing is followed by the joining process, where molten solder is directly applied to the joint area or heating is applied to melt the preplaced solder. Once the joint is cooled, all flux and solder residues must be removed.

- ***Soldering Materials***

For successful soldering, the base metal, the solder, and the flux materials must be chosen concurrently. Although most metals can be soldered, some are easier to solder than others: copper and copper alloys are the easiest base metals to solder, so are nickel and nickel alloys, while aluminum and its alloys, titanium, beryllium, and chromium are not normally soldered. The primary reason for our inability to solder materials in the last group is the difficulty encountered in removing the oxide film (i.e., fluxing) at the low temperatures of soldering.

Most commonly used solders are tin-lead alloys, with occasional addition of antimony (less than 2 to 3%). Since tin is an expensive material, manufacturers may choose to use lower percentages of tin in the tin-lead alloy, at the expense of higher melting points. The electronic industry prefers to use the eutectic composition due to its rapid solidification at the lowest melting point level.

Other solder materials include tin, silver, tin-zinc, tin-bismuth, and cadmium-silver. Tin-silver, for example, would be used for applications (intended product usages) with high service temperatures, since they have higher melting points (221 ºC) than do most tin-lead solders (183 ºC).

- ***Soldering Methods***

Soldering is a highly automated method of joining metal components. Most soldering methods can be classified according to the application of heat:

- conduction (e.g., wave soldering),
- convection (e.g., reflow soldering)
- radiation (e.g., infrared and laser beam soldering).

Wave soldering: also known as óflow solderingô, was patented by Fryôs Metals in 1956 and by the mid 1960s had become commonly used as a way of enhancing productivity and yield.

Wave soldering is an in-line process, during which the underside of the board is successively fluxed, preheated, immersed in liquid solder, and then cooled (Fig. 72).

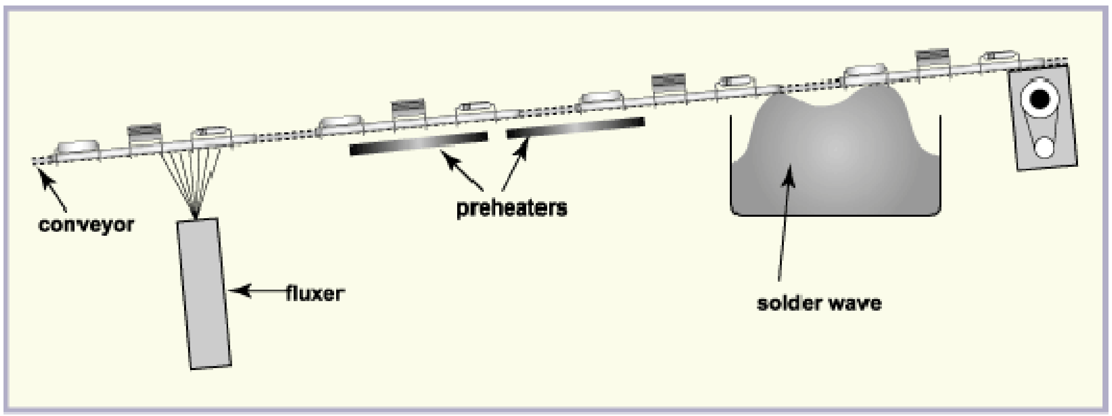


Fig. 72: Wave soldering process

Relative motion between board and solder is enhanced by the movement of the solder wave, and the surface kept free of oxide by drawing up fresh solder from underneath. In this automatic method, a pump located within a vat of solder (heated through conduction) creates an upward spout (a laminar flow wave). Exposed metal joints are passed over this wave in a continuous motion, where liquid solder attaches itself to the joint due to capillary forces.

Wave soldering is one of the most common techniques used in the electronics industry. It has numerous applications including component lead tinning, component manufacture, hybrid circuit assembly, and continuous wire tinning, but its main application is for soldering circuit board assemblies. The process for a through-hole component starts with selecting the part, cropping and forming it where necessary, inserting it into the board, and then applying molten solder to form the bond between the circuit board and component termination.

Through-hole components have to be held in position to prevent movement during handling and soldering, and especially to prevent them being pushed out of the hole during soldering. The upward force on the leads is a combination of their buoyancy (leads are less dense than solder) and the pressure of the solder wave. This ócomponent liftingô problem is most commonly seen with parts such as connectors, with multiple terminations and often little interference between the leads and the holes in the board. Mechanical retention may also be needed where the leads are either to be left long or to be sheared very short before or after soldering.

Reflow soldering: is a process in which a solder paste (a sticky mixture of powdered solder and flux) is used to temporarily attach one or several electrical components to their contact pads, after which the entire assembly is subjected to controlled heat, which melts the solder, permanently connecting the joint (Fig. 73). Heating may be accomplished by passing the assembly through a reflow oven or under an infrared lamp or by soldering individual joints with a hot air pencil.

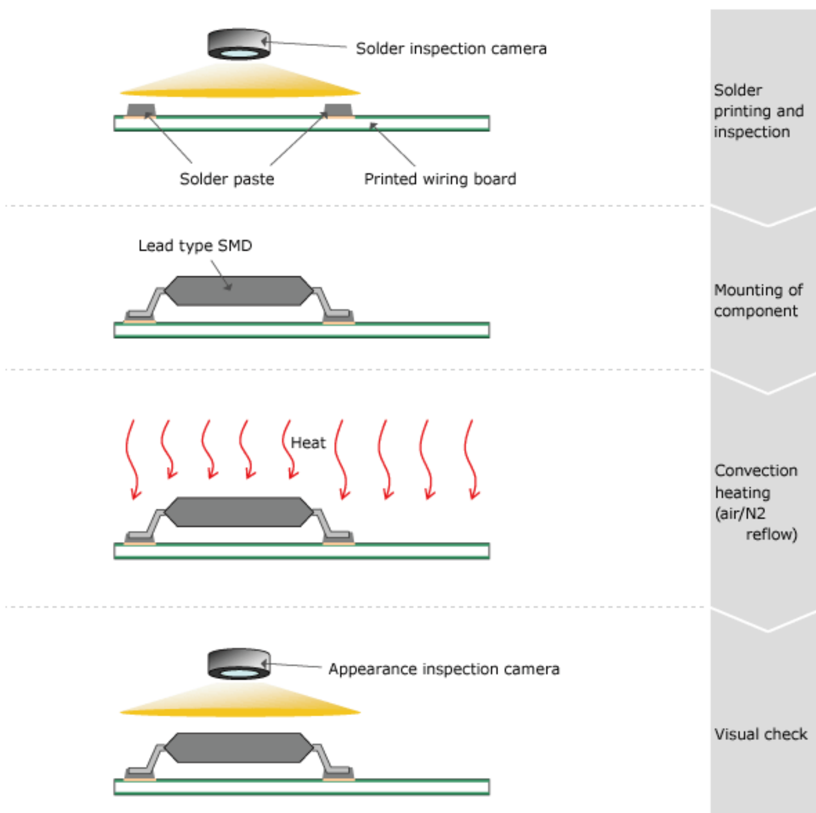


Fig. 73: Reflow soldering process

Reflow soldering is the most common method of attaching surface mount components to a circuit board, although it can also be used for through-hole components by filling the holes with solder paste and inserting the component leads through the paste. Because wave soldering can be simpler and cheaper, reflow is not generally used on pure through-hole boards. When used on boards containing a mix of SMT and THT components, through-hole reflow allows the wave soldering step to be eliminated from the assembly process, potentially reducing assembly costs.

Infrared reflow soldering: In this method, components are heated by emitted IR radiation (radiative heating) using an IR heater as the heat source (Fig. 74).

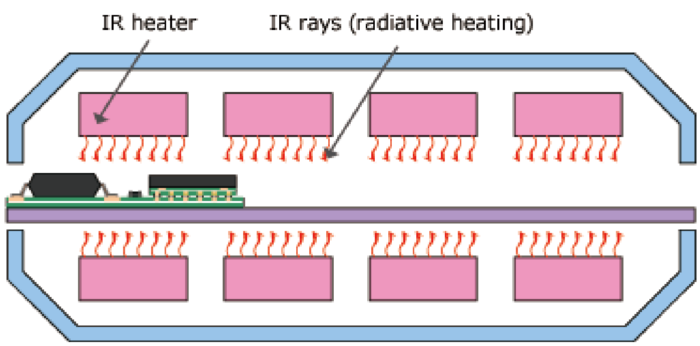


Fig. 74: Infrared reflow soldering

In infrared ovens, melting of preplaced solder is achieved via electromagnetic radiation in the far range of the 0.75 to 1000 µm infrared wavelength. Only 20 to 30% of heat in such ovens is provided by radiation. Convection provides the remaining percentage of heat, thus eliminating potential shadowing problems. Some infrared ovens also use inert gas atmospheres.

Vapor phase soldering: This convection based heat transfer method (developed in 1973 by Western Electric Company, U.S.A.) provides soldering ovens with excellent temperature control and uniformity of heating. A liquid vat (normally with fluorinated hydrocarbon fluid) is utilized to generate vapor with good oxidation resistance and fill a chamber, through which a product (usually PCBs) with preplaced solder moves.

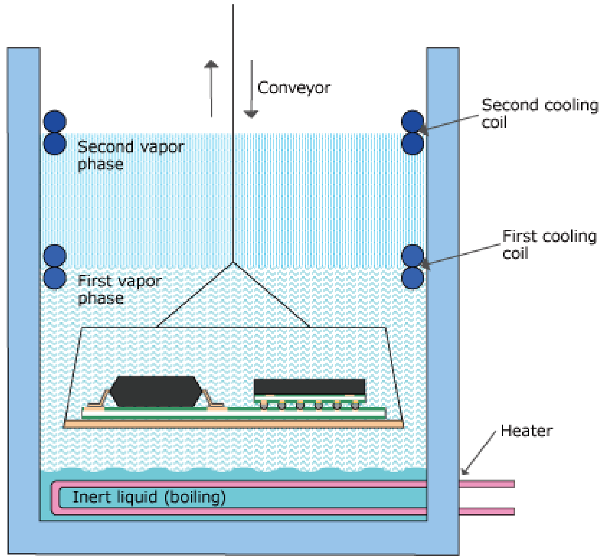


Fig. 75: Vapor phase soldering

The vapor, when in contact with the product, raises the temperature of the solder to the boiling temperature of the liquid in the vat and allows it to reflow and form the necessary joints (Fig. 75). As the joints are formed, the product is retrieved from the oven for fast solidification.

Chapter VI: *Materials Handling*

Materials handling is the field concerned with solving the pragmatic problems involving the movement, storage in a manufacturing plant or warehouse, control and protection of materials, goods and products throughout the processes of cleaning, preparation, manufacturing, distribution, consumption and disposal of all related materials, goods and their packaging.

The focus of material handling studies is on the methods, mechanical equipment, systems and related controls used to achieve these functions. The material handling industry manufactures and distributes the equipment and services required to implement material handling systems, from obtaining, locally processing and shipping raw materials to utilization of industrial feedstock in industrial manufacturing processes.

Material handling systems range from simple pallet rack and shelving projects, to complex conveyor belt and automated storage and retrieval systems (AS/RS). Material handling can also consist of sorting and picking, as well as automatic guided vehicles.

Material handling does not add value to the product but only cost. Thus the objective of material handling is the efficient movement of goods for the on-time delivery of correct parts in exact quantities to desired locations in order to minimize associated handling costs. It is not uncommon to have parts/subassemblies moving around a plant several kilometers prior to their shipment. Manufacturing plants must therefore eliminate all unnecessary part movements, as well as in-process inventories, for just-in-time (JIT) production.

Material handling equipment can be classified according to the movement mode: above-floor transportation (e.g., belt conveyors, trucks, etc.), on-floor transportation (e.g., chain conveyors), and overhead transportation (e.g., cranes). In the following sections, it will be reviewed industrial trucks, conveyors, and industrial robots as the primary mechanized/automated material handling equipment. It will also be briefly reviewed the automated storage and retrieval of goods in high-density warehouses, as well as the important issue of automatic part identification (including bar codes).

VI.1. Industrial Trucks

Industrial powered trucks are the most versatile and flexible materials handling devices in manufacturing. They can transport small or large loads over short distances in a plant with minimal restrictions on their movements.

Powered trucks are generally classified into two broad categories: lift trucks and tow tractors.

- ***Lift Trucks***

Powered (lift) fork trucks are the most common industrial trucks used in the manufacturing industry for the transportation of parts placed on pallets. The basic elements of a fork truck are the mast assembly ï a one-stage or multistage mechanism that lifts the forks, most commonly, through hydraulic power; the fork carriage ï a carriage that is mounted on the mast, to which the forks are attached, with a primary objective of preventing loads from falling backward once they have been lifted off the ground; and the forks ï the two forks can be of fixed configuration or with variable horizontal distance to accommodate varying load sizes.

The load capacity of forklift trucks is defined as the maximum weight carried at the maximum elevation of the forks. Typical forklifts can carry weights in the range of 1000 to 5000 kg at lift heights of up to 6 m and move at speeds of 5 to 10 km/h. A large number of forklift trucks are counterbalanced at their rear for increased load capacity and more secure transportation, though at the expense of a larger footprint and potential difficulty working in confined spaces.

The primary advantage of forklift trucks is their path independence. A trained driver can transport parts by following the shortest available route, though their being a driver-operated vehicle is also the greatest disadvantage of industrial trucks owing to increased costs.

- ***Tow Tractors***

A variety of wheeled vehicles are utilized in the manufacturing industry for towing (pulling) single/multi-trailer cart attachments. Most tractors are battery operated for maintaining clean-air environments within closed plants. The load carried can be palletized or (manually) placed directly on the trailer. The typical load-carrying capacity of electric-powered tow tractors ranges from

5000 to 25000 kg. As with forklift trucks, the primary disadvantage of tow tractors is their dependence on human drivers. Automated guided vehicles represent a potential answer to this disadvantage.

VI.2. Conveyors

Conveyors are a broad class of materials handling (conveying) equipment capable of transporting goods along fixed paths. Although conveyors are the least flexible material handling equipment (owing to their path inflexibility), they provide manufacturers with a cost-effective and reliable alternative.

Conveying equipment is generally classified as above-floor conveyors versus on-floor or overhead tow-line conveyors. Both classes allow horizontal and inclined conveying, while tow-line type conveyors also allow vertical conveying (e.g., bucket elevators).

- ***Above-Floor Conveyors***

Above-floor conveyors have been also classified as package handling conveyors owing to their primary application of transporting cartons, pallets, and totes. On the factory floor, they are utilized to transport (e.g., engine blocks, gearboxes, household items) from one assembly station to another. In a networked environment, where branching occurs, automatic identification devices must be utilized to route parts correctly to their destination along the shortest possible path.

Two types of above-floor conveyors can be used:

- *Roller conveyors* ï are line-restricted conveying devices comprising a set of space rollers mounted between two side frame members and elevated from the floor by a necessary distance. Rolling power can be achieved by having a moving flat belt underneath the rollers or a set of drive belts rotating the rollers individually, yielding speeds of up to 30 to 40 m/min.
- *Belt conveyors* ï are commonly used in the manufacturing industry for the transfer of individual (unpalletized) workpieces, as well as cartons/bins/etc. The highly durable, endless belt is placed in tension between two pulleys and normally operated in unidirectional motion. Belt conveyors can be inclined up to 30 to 40º and operate at speeds of 10 to 40 m/min, over lengths of 20 to 30 m, while carrying loads of up to 800 kg/m.

- ***On-Floor and Overhead Conveyors***

On-floor towline conveyors provide manufacturers with versatile transportation systems for conveying goods unsuitable (large, irregular geometry, etc.) for above-floor conveyors. They normally comprise one, two, or multiple chains running in parallel tracks (in shallow trenches). Goods can be directly placed on the chains or on pallets. Towline carts of a variety of sizes and shapes have also been used in on-floor conveying using chain conveyors. Traditionally, chain conveyors have been configured to operate along straight lines, horizontally and at low speeds (typically, 1 to 5 m/min for large loads and less than 25 to 30 m/min for small loads).

Overhead conveyors maximize utilization of three-dimensional workspaces. Although most are configured for the point-to-point transportation of unit loads directly mounted on the conveyor via hooks (e.g., automobile doors) or placed on suspension pallets, they can also provide a favorable environment for certain manufacturing applications, such as the on-the-fly spray-painting of workpieces. Overhead conveyors can operate horizontally or in inclined modes. The drive mechanisms employ chains or worm-screws. Occasionally, these conveyors also employ individually powered carriers capable of moving along monorails.

Overhead conveyors can reach speeds up to 80 to 100 m/min, though typically they operate in the range of 10 to 20 m/min.

VI.3. Industrial Robots

An industrial robot is defined as an automatically controlled, reprogrammable, multipurpose manipulator programmable in three or more axes. The field of robotics may be more practically defined as the study, design and use of robot systems for manufacturing (a top-level definition relying on the prior definition of robot).

Typical applications of robots include welding, painting, assembly, pick and place (such as packaging and palletizing), product inspection, and testing; all accomplished with high endurance, speed, and precision.

Many different variations of robots are available for use in industrial applications and are used to carry out repeated actions highly accurately and without variation. Robots require a control program to govern its velocity, direction, acceleration, deceleration and distance of movement at any time.

VI.3.1. Types of Robots

An Industrial robot consists of several links connected in series by linear, revolute or prismatic joints. At one end the robot will be fixed to a supporting base while the other is manipulated into position and equipped with a tool allowing it to perform a task.

Industrial robots are composed of the following parts:

- *Controller* ï a processing unit is connected to every industrial robot to regulate robot components, provide system networking, dynamic user control and program/teach.
- *Arm* ï this is the main moving part of the robot which is manipulated to deliver the end effector to the correct location.
- *Drive* ï the source of power to the arm motors/pumps.
- *End effector* ï the device on the end of the robot which is suitably equipped with tools required to perform a specific task once the arm has delivered it to the correct position. i.e., grippers, scalpel, spray gun, vacuum or even a vision camera.
- *Sensors* ï relay information about axis position, end effector orientation and surrounding environment.

There are a number of parameters which describe a robot as follows:

- *Number of Axis* – two axis are required to reach any point in a plane (x, y) and three axis are required to reach any point in space (x, y, z). Further axis of roll, pitch and yaw are required to control the orientation of the end of the robot.
- *Kinematics* ï the physical arrangement of rigid members and joints in the robot defining its possible motions.
- *Working envelope* ï the region of space within physical reach of the robot.
- *Carrying capacity* ï how much weight a robot can lift or move.
- *Speed* ï how quickly the robot can position itself as required.
- *Accuracy* ï how closely the robots position can be achieved.

- *Motion control* ï whether a robot need repeatedly move between pre-programmed positions as it sees best or be continuously controlled in orientation and velocity to follow a predetermined path in space.
- *Power source* ï be it electric motors or hydraulic actuators.
- *Drive* ï motors can be geared to the joints or direct drive.

The most commonly used robot configurations are

- ***Cartesian Coordinate Robot***

A Cartesian coordinate robot (Fig. 76) has three linear axes of control (x, y, z). Cartesian coordinate robots with the horizontal member supported at both ends are sometimes called Gantry robots and can be quite large in size.

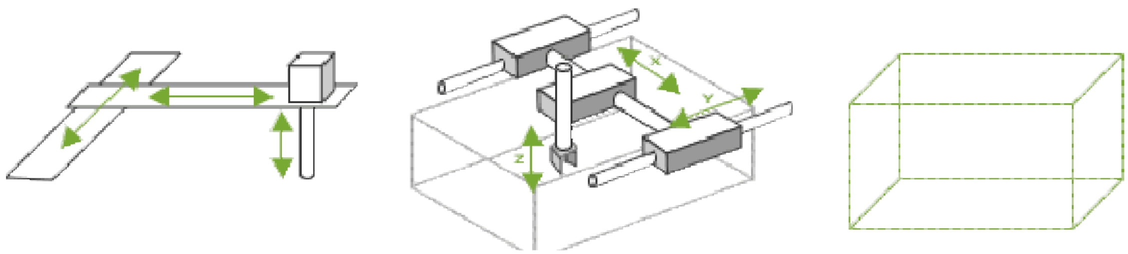


Fig. 76: Cartesian coordinate robot

- ***Cylindrical Robot***

A cylindrical robot (Fig. 77) has two linear axis and one rotary axis around its origin.

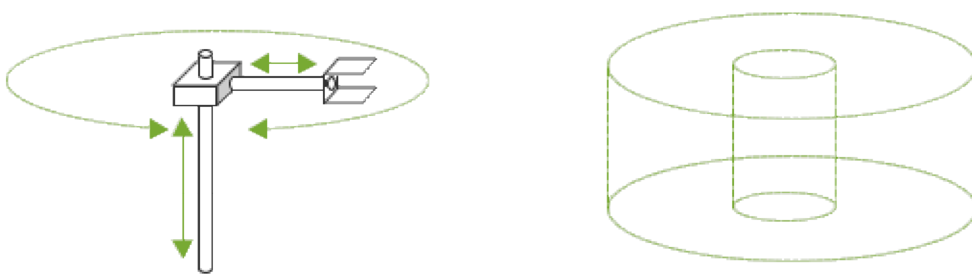


Fig. 77: Cylindrical Robot

- ***Spherical / Polar Robot***

A spherical or polar robot (Fig. 78) has one linear axis and two rotary axes.

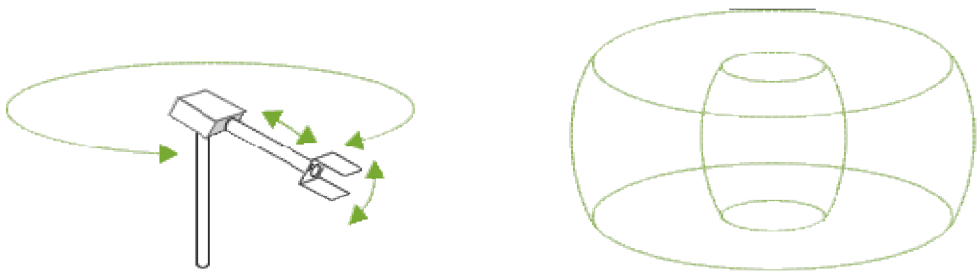


Fig. 78: Spherical/polar robot

- ***SCARA Robot***

SCARA (Selective Compliance Assembly Robot Arm) is a particular robot design developed in the late 1970's in Japan. The basic configuration of a SCARA (Fig. 79) is a four degree-of-freedom robot with horizontal positioning accomplished by a combined Theta 1 and Theta 2 motion, much like a shoulder and elbow held perfectly parallel to the ground. SCARA robots are known for their fast cycle times, excellent repeatability, good payload capacity and large workspace.

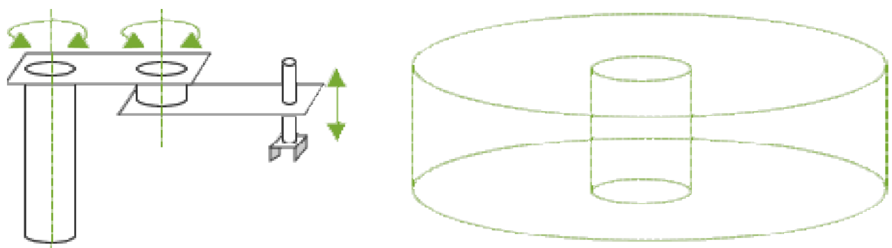


Fig. 79: SCARA robot

- ***Picker / Delta Parallel Robots***

Picker or delta parallel robots (Fig. 80) use three parallelograms to build a robot with three translational and one rotational degree of freedom. The parallelograms ensure consistent orientation of one end of the arm with respect to the other, while the rotational axis is provided at the end effector. As the arms are parallel with each other, the weight of the load is distributed over all three arms and similarly any errors are averaged over the legs instead of built up as with serial robots. However the rotational and positioning capabilities are closely linked complicates the delivery and orientation of the end effector.

Fig. 80: Picker or delta parallel robots

- ***Articulated / Jointed-Arm Robots***

Articulated or joint-arm robots (Fig. 81) are the most versatile robots available closely mimic the natural form of the human arm. There are two variations of these robots based on the number of axis used. A three axis jointed arm has three rotary axis, one around the base and on each of the joints (A1, A2 & A3). In terms of a human arm this can be compared to the shoulder, bicep and forearm but without the use of a wrist. A six-axis robot does include the axis of the wrist (A4, A5 & A6), known as pitch, roll and yaw. With thess extra axis this robot can deliver the end effector to any point in space in any orientation.

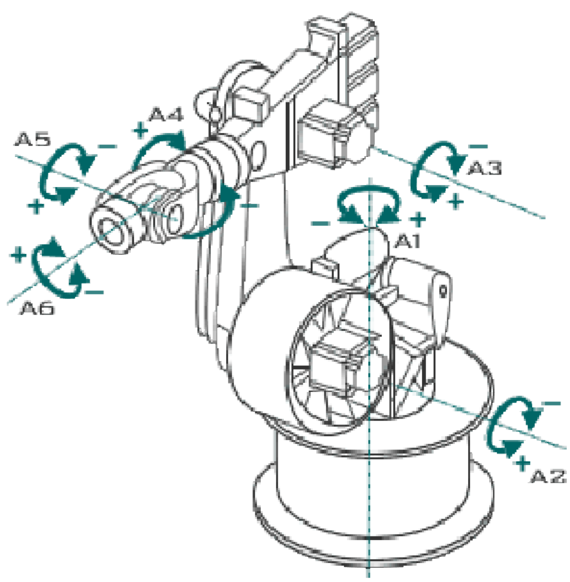


Fig. 81: Articulated or joint-arm robot

- ***Snake Arm Robots***

Snake arm robots (Fig. 82) are flexible manipulators that get their name from their ability to follow the front of the robot around and through obstacles in a snake-like fashion. They gain access to areas otherwise in accessible to allow operations such as inspection, welding and positioning to take place. They are constructed in much the same way as the human spine via a number of interconnected vertebrae. Drive wires are used like tendons, terminating at different points along the length providing the ability to pull the body in a certain direction, individually adjusting the curvature of the section where the wire terminates. The length of the wires is controlled by a series of servo-actuators within the drive unit at the base of the robot arm.

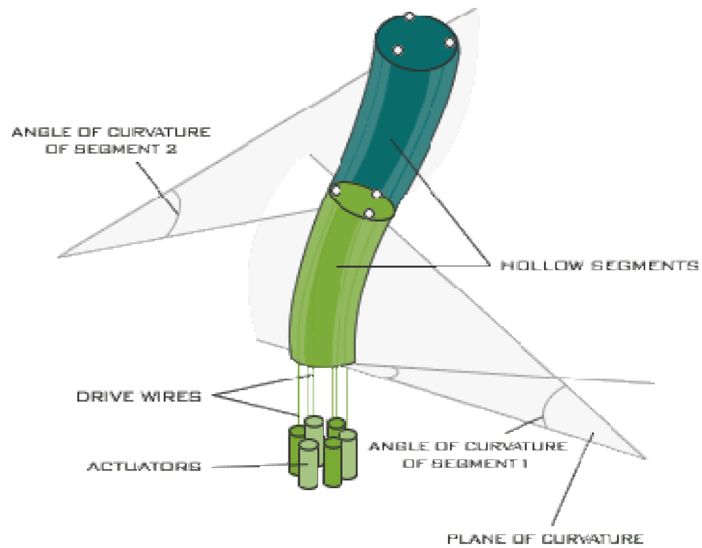


Fig. 82: Snake arm robots

In the context of general robotics, most types of robots would fall into the category of robotic arms.

Robots exhibit varying degrees of autonomy. Some robots are programmed to faithfully carry out specific actions over and over again (repetitive actions) without variation and with a high degree of accuracy. These actions are determined by programmed routines that specify the direction, acceleration, velocity, deceleration, and distance of a series of coordinated motions. Other robots are much more flexible as to the orientation of the object on which they are operating or even the task that has to be performed on the object itself, which the robot may even need to identify. For example, for more precise guidance, robots often contain machine vision sub-systems acting as their visual sensors, linked to powerful computers or controllers. Artificial intelligence, or what passes for it, is becoming an increasingly important factor in the modern industrial robot.

VI.3.2. Robot Programming and Interfaces

The setup or programming of motions and sequences for an industrial robot is typically taught by linking the robot controller to a laptop, desktop computer or (internal or Internet) network.

A robot and a collection of machines or peripherals is referred to as a workcell, or cell. The various machines are 'integrated' and controlled by a single computer or PLC. How the robot interacts with other machines in the cell must be programmed, both with regard to their positions in the cell and synchronizing with them.

- ***Software***

The computer is installed with corresponding interface software. The use of a computer greatly simplifies the programming process. Specialized robot software is run either in the robot controller or in the computer or both depending on the system design.

There are two basic entities that need to be taught (or programmed): positional data and procedure. For example in a task to move a screw from a feeder to a hole the positions of the feeder and the hole must first be taught or programmed. Secondly the procedure to get the screw from the feeder to the hole must be programmed along with any I/O involved, for example a signal to indicate when the screw is in the feeder ready to be picked up. The purpose of the robot software is to facilitate both these programming tasks.

- ***Teaching the robot positions***

This may be achieved by different ways:

- *Positional commands:* The robot can be directed to the required position using a GUI or text based commands in which the required x-y-z position may be specified and edited.

- *Teach pendant*: Robot positions can be taught via a teach pendant. This is a handheld control and programming unit. The common features of such units are the ability to manually send the robot to a desired position, or "inch" or "jog" to adjust a position. They also have a means to change the speed since a low speed is usually required for careful positioning, or while test-running through a new or modified routine. A large emergency stop button is usually included as well. Typically once the robot has been programmed there is no more use for the teach pendant.

- *Lead-by-the-nose:* Is a technique offered by many robot manufacturers. In this method, one user holds the robot's manipulator, while another person enters a command which de-energizes the robot causing it to go limp. The user then moves the robot by hand to the required positions and/or along a required path while the software logs these positions into memory. The program can later run the robot to these positions or along the taught path. This technique is popular for tasks such as paint spraying.

- *Offline programming*: Is where the entire cell, the robot and all the machines or instruments in the workspace are mapped graphically. The robot can then be moved on screen and the process simulated. A robotics simulator is used to create embedded applications for a robot, without depending on the physical operation of the robot arm and end effector. The advantage of robotics simulation is that it saves time in the design of robotics applications. It can also increase the level of safety associated with robotic equipment since various "what if" scenarios can be tried and tested before the system is activated. Robot simulation software provides a platform to teach, test, run, and debug programs that have been written in a variety of programming languages.

- *Robot simulation tools*: allow for robotics programs to be conveniently written and debugged off-line with the final version of the program tested on an actual robot. The ability to preview the behavior of a robotic system in a virtual world allows for a variety of mechanisms, devices, configurations and controllers to be tried and tested before being applied to a "real world" system. Robotics simulators have the ability to provide real-time computing of the simulated motion of an industrial robot using both geometric modeling and kinematics modeling.

- *Others:* In addition, machine operators often use user interface devices, typically touch screen units, which serve as the operator control panel. The operator can switch from program to program, make adjustments within a program and also operate a host of peripheral devices that may be integrated within the same robotic system. These include end effectors, feeders that supply components to the robot, conveyor belts, emergency stop controls, machine vision systems, safety interlock systems, bar code printers and an almost infinite array of other industrial devices which are accessed and controlled via the operator control panel.

The teach pendant or PC is usually disconnected after programming and the robot then runs on the program that has been installed in its controller. However a computer is often used to 'supervise' the robot and any peripherals, or to provide additional storage for access to numerous complex paths and routines.

VI.4. Automated Storage and Retrieval

The storage of goods until they are required for a manufacturing operation or shipment to a customer is commonly referred to as warehousing. The three common objectives of warehousing are:

- ease of accessibility for random retrieval,
- effective protection of goods while they are stored and transported,
- maximum utilization of space.

There are a variety of racks that can be used in the construction of high-density storage areas. Such structures could be as high as 20 to 30 meters and be totally automated in terms of storage of goods and their random retrieval based on an order issued by the warehousing computer ï automated storage and retrieval systems (AS/RS).

Storage and retrieval equipment in high-density warehouses can be categorized into single-masted (single-column), double-masted, and human-aboard machines (stacker canes). Single-masted and double-masted machines are normally supported from the ceiling for accurate vertical alignment. All such machines are equipped with telescopic extraction devices for the loading/unloading of unit loads onto/from the racks based on an address defined by the warehousing computer.

VI.5. Identification and Tracking of Goods

Effective material handling in flexible manufacturing systems requires automatic identification and tracking of goods that are stationary or in motion.

This information must be transferred into a computer that oversees the transportation of goods in a timely manner.

Some exemplary scenarios that necessitate automatic identification are listed below as a preamble to the descriptions of available technologies:

- Unit loads (cartons, bins, pallets, etc.) moving on a conveyor network must be identified for correct branching.
- A product arriving at an assembly substation must be identified for the correct assembly of parts by human or robotic operators.
- A product arriving at a warehouse must be correctly identified for its automatic storage.

Automatic identification can be carried out by directly observing the geometry of the object or by indirectly reading an alphanumeric code attached to the object or onto the pallet/fixture carrying it. The former is, normally, carried out using a computer vision system or a collection of electro-optical or electromagnetic sensors that can detect a limited number of features on the object.

Part identification through computer vision is a complex procedure and cannot be effectively utilized in high-volume, high-speed applications. Identification through individual noncontact sensors, on the other hand, can only differentiate among a limited number of object features.

- ***Bar Codes***

Bar codes are the most commonly used identifiers of unit loads in manufacturing environments. Their primary advantage is the near-impossibility of incorrect identification ï for most codes, a less than one in a million chance. Even if a bar-code scanner does not succeed in reading a code owing to improper printing or dirt, it will almost never read it as a different existing code.

A bar code is a collection of vertical printed bars (white and black) of two distinct thicknesses that form a constant-length string. Alphanumeric information is represented by assembling (combinatorial) different fixed-length subsets of vertical bars (i.e., characters) into a code. Almost all bar-code strings are provided with a check digit at their end for minimizing the occurrence of errors.

The 3 of 9 bar-code (Fig. 83) is the most commonly used coding technique in manufacturing. A 3 of 9 bar-code character utilizes 3 wide and 6 narrow bars (black or white) to define a character. The symbology comprises the numbers 0 to 9, the letters A to Z, and six additional symbols, for a total of 43 characters. The Universal Product Code (UPC) symbology, on the other hand, is an all-numeric bar code, in which each digit is represented by 2 black and 2 white (narrow or wide) bars.

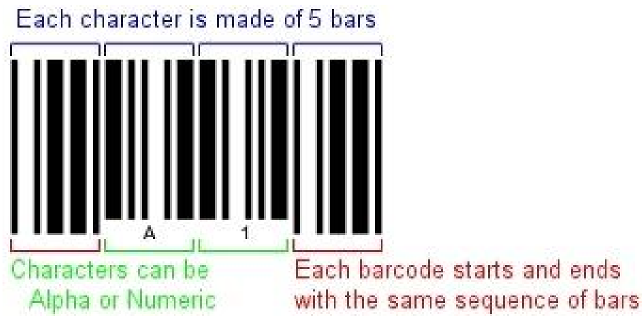


Fig. 83: 3 of 9 bar-code

Bar codes printed on the highest possible quality printers are normally attached onto cartons/boxes that contain the goods or onto the pallets/fixtures that carry the goods and only very rarely onto the object itself. They must be placed on locations that are visible to the bar-code readers, preferably on the flattest parts of the goods/pallets/etc.

Bar-code readers (also known as óóscannersôô) can be of the handheld type or the fixed-in-place type (e.g., stationed on the side of the conveyor). They must be placed at correct heights for effective reading. The reader scans through the bar code horizontally utilizing a light beam of circular cross section (reflected back for interpretation) with a diameter that is much smaller than the height of the bars. This relative dimensionality allows the bar-code reader to scan codes that are not well placed ï misaligned and/or above or below their expected location.

In certain circumstances, when the environmental and product constraints do not allow the use of optical devices, manufacturers have to use identifiers based on electromagnetic or RF-emission technologies (e.g., magnetic cards, tags). Such active (battery-powered) tags (transponders) are normally attached to the carriers of the goods (boxes, bins, pallets) that are reusable through reprogramming of the tag or the identifier (or both) for new goods.

Chapter VII: *Quality Control of Manufacturing*

The definition of quality has evolved over the past century from meeting the engineering specifications of the product (i.e., conformance), to surpassing the expectations of the customer (i.e., customer satisfaction).

The management of quality, according to J. M. Juran, can be carried out via three processes: planning, control, and improvement.

Quality planning includes the following steps: identifying the customer's needs/expectations, designing a robust product with appropriate features to satisfy these needs, and establishing (manufacturing) processes capable of meeting the engineering specifications.

Quality control refers to the establishment of closed loop control processes capable of measuring conformance (as compared to desired metrics) and varying production parameters, when necessary, to maintain steady-state control.

Quality improvement requires an organization's management to maximize efforts for continued increase of product quality by setting higher standards and enabling employees to achieve them. A typical goal would be the minimization of variations in output parameters by increasing the capability of the process involved by either retrofitting existing machines or acquiring better machines.

Cost of quality management has always been an obstacle to overcome in implementing effective quality control procedures. In response to this problem, management teams of manufacturing companies have experimented over the past several decades with techniques such as (on-line) statistical process control versus (postprocess) acceptance by sampling, versus 100% inspection/testing and so on.

No matter how great is the cost of quality control implementation, engineers must consider the cost of manufacturing poor quality products. These lead to increased amounts of rejects and reworks and thus to higher production costs. Dissatisfaction causes customers to abandon their loyalty to the brand name and eventually leads to significant and rapid market share loss for the company. Loyalty is more easily lost than it is gained.

It has been erroneously argued that high-quality products can only be purchased at high prices. Such arguments have been put forward by companies who scrap their products that fall outside their specification limits and pass on this cost to the customers by increasing the price of their within-limits goods. In practice, price should only be proportional to the performance of a product and not to its quality.

VII.1. Inspection for Quality Control

Inspection has been defined in the quality control literature as the evaluation of a product or a process with respect to its specifications ï verification of conformance to requirements. The term *testing* has also been used in the literature as synonym with inspection.

Herein, testing refers solely to the verification of expected (designed) functionality of a product/process, whereas inspection further includes the evaluation of the functional/nonfunctional features. Consequence, testing is a subset of inspection.

The inspection process can include the measurement of variable features or the verification of the presence or absence of features/parts on a product. Following an inspection process, the outcome of a measurement can be recorded as a numeric value to be used for process control or simply as satisfying a requirement.

With the advancements in instrumentation technologies, two significant trends have been developing in manufacturing quality control:

- automated versus manual inspection,
- on-line versus postprocess inspection.

The common objective to both trends may be defined as reliable and timely measurement of features for effective feedback-based process control versus post-manufacturing product inspection.

Tolerances are utilized in the manufacturing industry to define acceptable deviations from a desired nominal value for a product/process feature. It has been convincingly argued that the smaller the deviation, the better the quality and thus the less the quality loss. Tolerances are design specifications, and the degree of satisfying such constraints is a direct function of the (statistical) capability of the process utilized to fabricate that product.

Prior to a brief review of different inspection strategies, one must note that the measurement instruments should have a resolution (i.e., the smallest unit value that can be measured) an order of magnitude better than the resolution used to specify the tolerances at hand. Furthermore, the repeatability of the measurement instruments (i.e., the measure of random errors in the output of the instrument, also known as precision) must also be an order of magnitude better than the resolution used to specify the tolerances at hand.

VII.1.1. Inspection Strategies

The term inspection has had a negative connotation in the past two decades owing to its erroneous classification as a post-process, off-line product examination function based solely on statistical sampling. Inspection should actually be seen as conformance verification process, which can be applied based on different strategies ï some better than others. However, certain conclusions always hold true: on-line (in-process) inspection is better than post-process inspection; 100% inspection is better than sampling, and process control is better than product inspection.

- ***On-line inspection***

It is desirable to measure product features while the product is being manufactured and to feed this information back to the process controller in an on-line manner. For example, an electro-optical system can be used to measure the diameter of a shaft, while it is being machined on a radial grinder, and to adjust the feed of the grinding wheel accordingly. However, most fabrication processes do not allow in-process measurement owing to difficult manufacturing conditions and/or the lack of reliable measurement instruments. In such cases, one may make intermittent (discrete) measurements, when possible, by stopping the process or waiting until the fabrication process is finished.

- ***Sampling***

If a productôs features cannot be measured on-line, owing to technological or economic reasons, one must resort to statistical sampling inspection. The analysis of sample statistics must still be fed back to the process controller for potential adjustments to input variables to maintain in-control fabrication conditions. Sampling should only be used for processes that have already been verified to be in control and stable for an acceptable initial buildup period, during which 100% inspection may have been necessary regardless of economic considerations.

- ***Source inspection***

It has been successfully argued that quality can be better managed by carrying out inspection at the source of the manufacturing, that is, at the process level, as opposed to at (post-process) product level.

For fabrication, this would involve the employment of effective measurement instruments as part of the closed-loop process-control chain. For assembly, this would involve the use of devices and procedures that would prevent the assembly of wrong components and ensure the presence of all components and subassemblies.

VII.1.2. Measurement Techniques

Measurement is a quantification process used to assign a value to a product/process feature in comparison to a standard in a selected unit system (SI metric versus English, U.S. customary measurement systems).

The term *metrology* refers to the science of measurement in terms of the instrumentation and the interpretation of measurements. The latter requires a total identification of sources of errors that would affect the measurements. It is expected that all measurement devices will be calibrated via standards that have at least an order of magnitude better precision (repeatability). Good calibration minimizes the potential of having (nonrandom) systematic errors present during the measurement process. However, one cannot avoid the presence of (noise-based) random errors; one can only reduce their impact by repeating the measurement several times and employing a software/hardware filter and maintaining a measurement environment that is not very sensitive to external disturbances.

Variability in a processô output, assuming an ideal device calibration, is attributed to the presence of random mechanisms causing (random) errors. As introduced above, this random variability is called repeatability, while accuracy represents the totality of systematic (calibration) errors and random errors. Under ideal conditions, accuracy would be equal to repeatability.

Since the objective of the measurement process is to check the conformance of a product/process to specifications, the repeatability of the measurement instrument should be at least an order of magnitude better than the repeatability of the production process. Thus random errors in measuring the variability of the output can be assumed to be attributable primarily to the capability (i.e., variance) of the production device and not to the measurement instrument.

VII.2. Quality Management Systems

A *quality management system* (QMS) is a collection of business processes focused on achieving quality policy and quality objectives to meet customer requirements. It is expressed as the organizational structure, policies, procedures, processes and resources needed to implement quality management.

Early systems emphasized predictable outcomes of an industrial product production line, using simple statistics and random sampling. By the 20th century, labor inputs were typically the most costly inputs in most industrialized societies, so focus shifted to team cooperation and dynamics, especially the early signaling of problems via a continuous improvement cycle. In the 21st century, QMS has tended to converge with sustainability and transparency initiatives, as both investor and customer satisfaction and perceived quality is increasingly tied to these factors.

Of all QMS regimes, the ISO 9000 family of standards is probably the most widely implemented.

The ISO 9000 family of quality management systems standards is designed to help organizations ensure that they meet the needs of customers and other stakeholders while meeting statutory and regulatory requirements related to a product.

ISO 9000 deals with the fundamentals of quality management systems, including the eight management principles upon which the family of standards is based. The ISO 9000:1994 family of standards allowed organizations to choose one of three standards, tailored for specific quality management system applications, ISO 9001, ISO 9002, and ISO 9003 for registration. All organizations, however, were encouraged to implement the fourth standard, ISO 9004, which stated the exact quality management requirements that would lead to certification under one of the three quality assurance standards, ISO 9001, ISO 9002, or ISO 9003.

ISO 9001 deals with the requirements that organizations wishing to meet the standard must fulfill.

Third-party certification bodies provide independent confirmation that organizations meet the requirements of ISO 9001. Over one million organizations worldwide are independently certified, making ISO 9001 one of the most widely used management tools in the world today. However, the ISO certification process has been criticized as being wasteful and not being useful for all organizations.

ISO does not certify organizations itself. Numerous certification bodies exist, which audit organizations and, upon success, issue ISO 9001 compliance certificates. Although commonly referred to as "ISO 9000" certification, the actual standard to which an organization's quality management system can be certified is ISO 9001:2008.

Many countries have formed accreditation bodies to authorize the certification bodies. Both the accreditation and the certification bodies charge fees for their services. The various accreditation bodies have mutual agreements with each other to ensure that certificates issued by one of the accredited certification bodies (CB) are accepted worldwide. Certification bodies themselves operate under another quality standard, ISO/IEC 17021, while accreditation bodies operate under ISO/IEC 17011.

An organization applying for ISO 9001 certification is audited based on an extensive sample of its sites, functions, products, services and processes. The auditor presents a list of problems (defined as "nonconformities", "observations", or "opportunities for improvement") to management. If there are no major nonconformities, the certification body will issue a certificate. Where major nonconformities are identified, the organization will present an improvement plan to the certification body (e.g., corrective action reports showing how the problems will be resolved); once the certification body is satisfied that the organization has carried out sufficient corrective action, it will issue a certificate. The certificate is limited by a certain scope and will display the addresses to which the certificate refers.

An ISO 9001 certificate is not a once-and-for-all award, but must be renewed at regular intervals recommended by the certification body, usually once every three years. There are no grades of competence within ISO 9001: either a company is certified (meaning that it is committed to the method and model of quality management described in the standard) or it is not. In this respect, ISO 9001 certification contrasts with measurement-based quality systems.

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