CHAPTER 5

General selection of primary production processes

5.1 FROM DESIGN TO PROCESS PLANNING

The process planner defines in detail the process that will transform raw material into the desired shape. The shape is defined by the product designer and is expressed in engineering drawings and GDT – geometric dimensioning and tolerances. The process planner is bound by the defined drawing.

The designer is a problem solver who applies such fields as physics, mathematics, hydraulics, pneumatics, electronics, metallurgy, strength of materials, dynamics, magnetics and acoustics in order to find a solution, namely, the new product. His/her main responsibility is to design a product that meets customer specifications. A parallel target is to design a high-quality, low-cost product.

There is no single solution to a design problem, but rather a variety of possible solutions which surround a broad optimum. The solution can come from different fields of engineering and apply different concepts. The designer is bound by constraints that arise from physical laws, the limits of available resources, the time factor, company procedures and government regulations.

Among all these possible solutions, the designer selects the most suitable.

To insure against failure, the designer provides a margin of safety. Strength failures, for instance, are protected by a factor of safety. For mechanical components, it is customary to use a factor from 4 to 40. To insure against potential errors in manufacturing, the designer specifies the permissible deviations, that is, the acceptable range of tolerances. All too often, designers specify excessively tight tolerances in order to be conservative and avoid risk.

Product designers are not process planners. However, what they have in mind during the design stage significantly affects the manufacturing process and the process planning. They do not go into details of the manufacturing process, but usually work by intuition. However, parts that were designed with a specific manufacturing process in mind might turn out to be very difficult to manufacture if the process has to be changed. In such cases, it should be remembered that parts are designed subject to functional, strength or manufacturing constraints. Part drawing should always by seen as a constraint; it might be an artificial constraint if the manufacturing process is the controlling factor in part design.

Studies have indicated that the cost of the engineering stages, i.e. product design, detail design, testing and process planning, is about 15% of the product cost, while the production stage accounts for 85%. However, since the committed cost of the product is about 90% established in the engineering stages, it is worthwhile not to rush but to increase thinking time in design, before making decisions.

The product designer should bear in mind the manufacturing process that will produce the designed part. Each manufacturing process has its advantages, capabilities and limitations. The cost of a part can be kept to a minimum if its features, dimensions and tolerances match the capabilities of one of the available processes. Otherwise, the cost might be excessively high or the production might even be impossible. Designers do not define the process plan, but rather steer toward utilization of existing processes, preferably to one available in their own plant.

5.2 CLASSIFICATION OF MANUFACTURING PROCESSES

Manufacturing processes can be broadly divided into the following categories.

5.2.1 **Forming from liquid (casting, molding)**

To form a part by liquid casting or molding, the raw material is heated to its liquid state and then poured, or pushed, into a mold of the desired form (Fig. 5.1).

This is an economical method of producing complicated shapes. However, it is susceptible to internal porosity resulting from shrinkage and the presence of gas. The flow of material in the mold in thin channels is also a serious problem

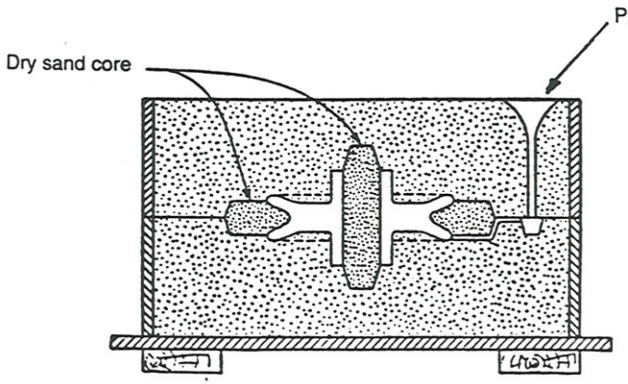


Fig. 5.1 Cross-section view of a mold for sand casting.

that should be considered in the design. The cost of the mold is high, and the dimensions and surface finish often cannot be kept to tight tolerances. On the whole, casting is a good process for mass production.

5.2.2 Forming from solid by deformation

This type of forming can be divided into three subgroups:

1. *hot working*, including hot rolling, forging and extrusion;
2. *cold working*, stamping, bending, spinning, stretch forming, shearing, cold rolling, extrusion, deep drawing etc.; and
3. *forming from powder*, such as powder metallurgy and plastic molding.

Rolling (Fig. 5.2) is the cheapest method of shaping materials. Rolling into bars, plates or sheets is executed by passing the ingot between rolls that grip the material and draw it through, compressing it and reducing its cross-section, which remains constant while its length increases.

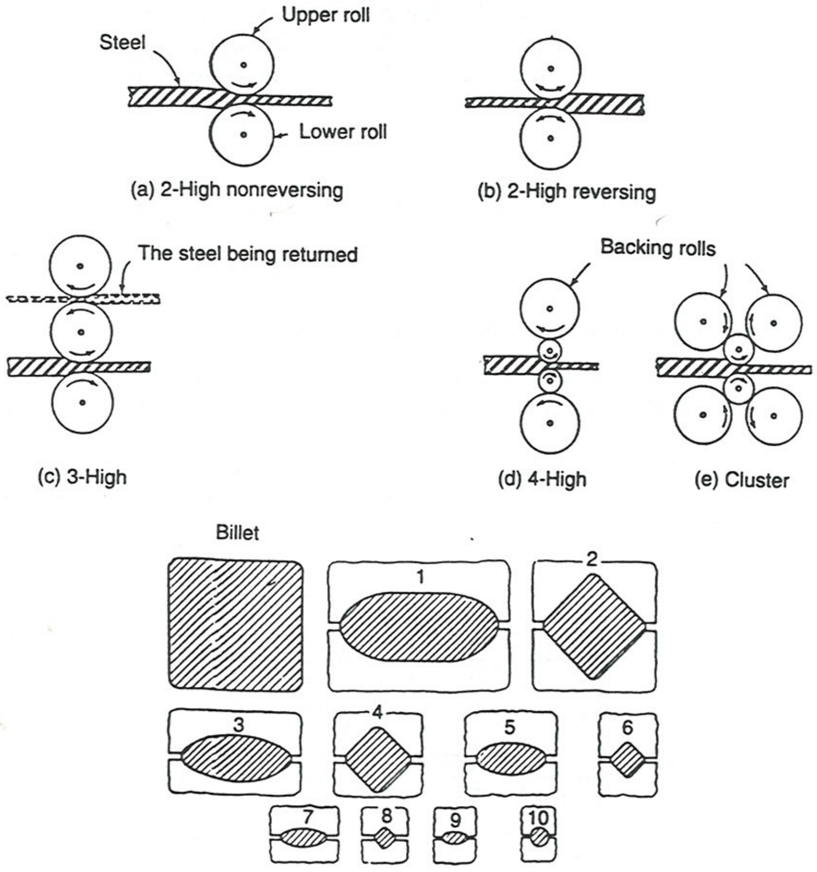


Fig. 5.2 The arrangement and shape of the rolls on a rolling mill.

Not all materials are formable. The process is limited to simple shapes and is susceptible to changes in such material properties as tensile strength, hardness and ductility. Cracks developing during the process can be a problem. Dimensions can be kept to tight tolerances.

Forging (Fig. 5.3) is defined as the working of a piece of material into a desired shape by hammering or pressing, usually after heating, to improve its plasticity. The material may be shaped by drawing it out, which decreases the cross-sectional area and increases the length; by upsetting, which increases the cross-sectional area and decreases its length; or by squeezing it in close impression dies.

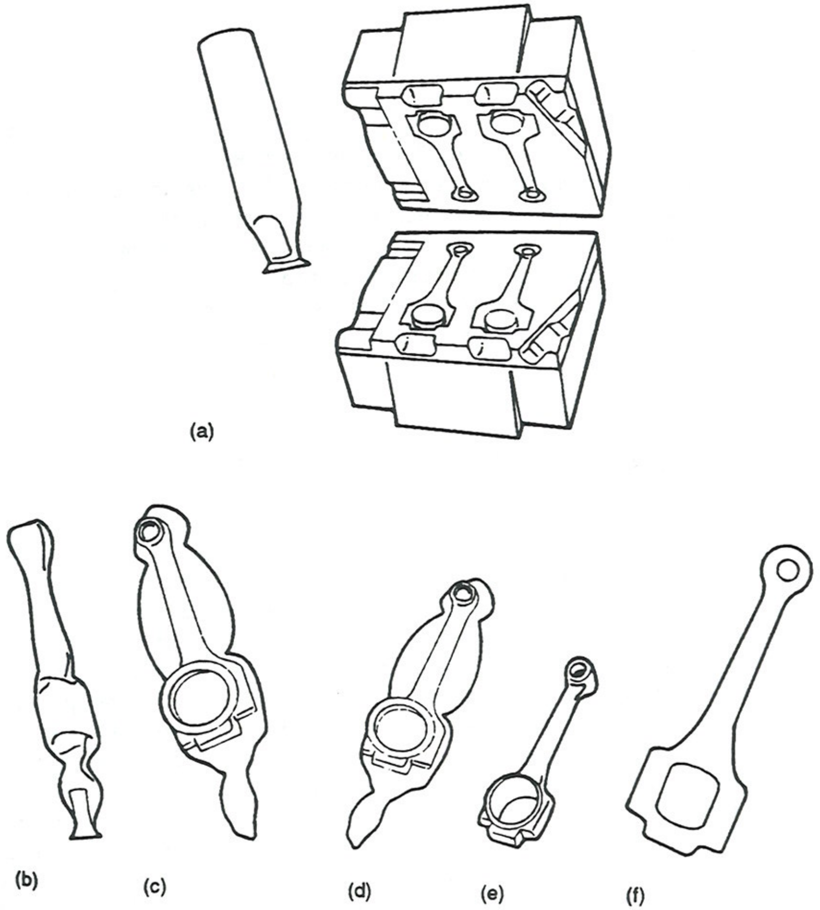


Fig. 5.3 Dies for drop-forging.

Forging has better mechanical properties than casting, so parts that have to withstand severe stresses should be made by forging. Forging has its disadvantages, however. Die costs are generally higher than casting and molds; many intricate and cored shapes possible in casting cannot be forged; closed impression die forging is limited with respect to size, and dimension control is difficult due to shrinkage and die wear, or the die may strike out of alignment.

Press work of cold material may be used for shearing, **stamping** or drawing (Fig. 5.4). Close dimensional control may be achieved, although special dies are required for each part. Bending along straight lines (Fig. 5.5) uses standard brake press tooling; this may keep close dimensional control, although it has limitations as regards the shape produced by this method.

Spinning (Fig. 5.6) and **stretch forming** (Fig. 5.7) are better suited for small quantity production; in fact some of the work cannot be done by other processes. Thin wall dimensions can be controlled, and if done properly no change in material properties will occur.

Powder metallurgy (sintering) and **plastic molding** (Fig. 5.8) is a technique by which material in powder form is injected into a die of the required shape. It is possible to combine metallic powder with nonmetallic powder to produce useful material combinations. The chemical analysis of the part is closely controlled, although not all materials can be processed. A high production rate can be obtained with this technique, although the initial cost of the dies is high. Dimension control is difficult due to shrinkage and die wear, or the die may strike out of alignment. A good surface finish can be maintained. There is a size limitation due to press and die requirements, and there is a problem with the flow of material in the mold in thin channels, which should be considered at the design stage. There are specific rules to follow when designing a part to be produced by this technique. Intricate shapes cannot be produced, and complicated dies may be required for some parts that appear suitable for this

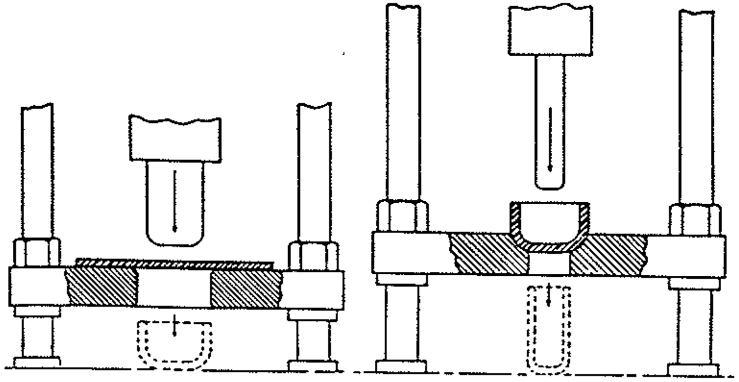


Fig. 5.4 Cold drawing.

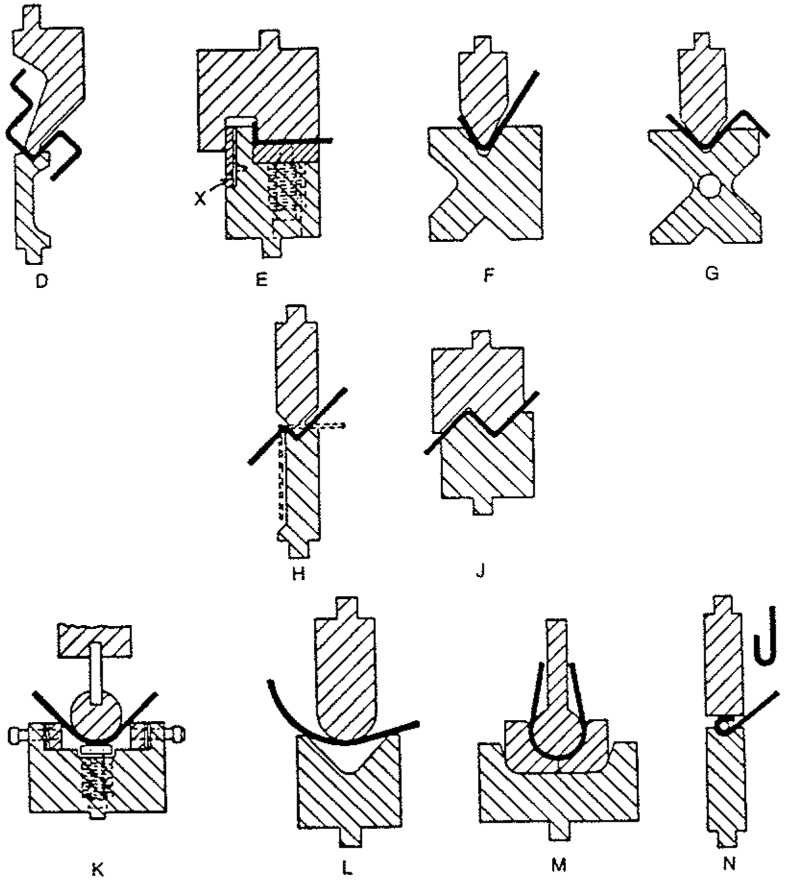


Fig. 5.5 Standard bending dies used on brake press.

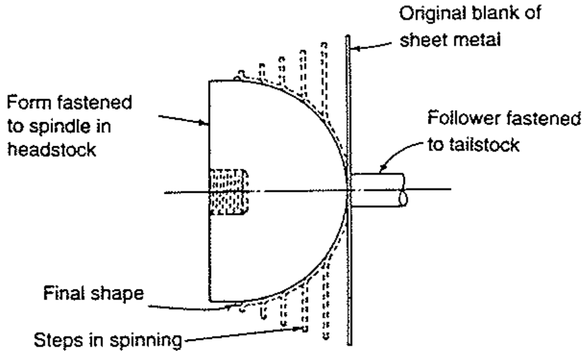


Fig. 5.6 Spinning operation.

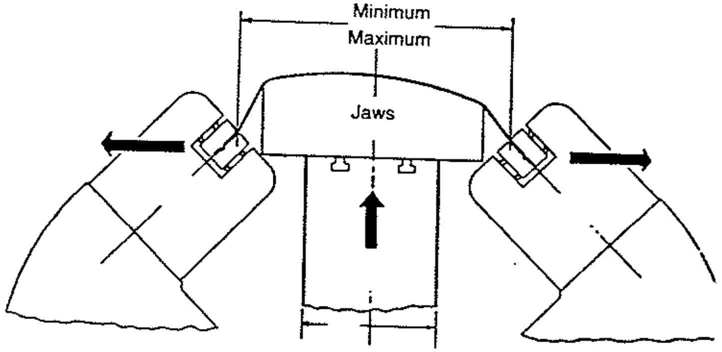


Fig. 5.7 Stretch forming.

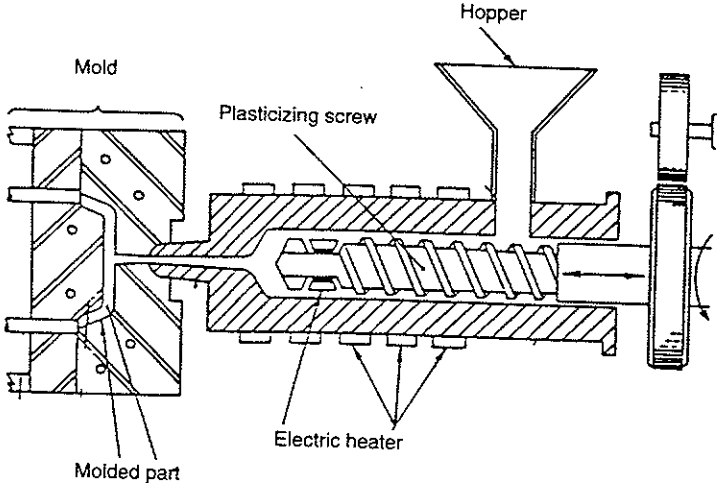


Fig. 5.8 Plastic molding machine.

technique. Some materials, such as hard metals, can only be produced by sintering because of their refractory properties.

5.2.3 Forming from solid by material removal

This technique encompasses all types of cutting operations that transform the workpiece into its final geometry by removing pieces of material from it. Some of the most common machining processes are illustrated in Fig. 5.9, and described below.

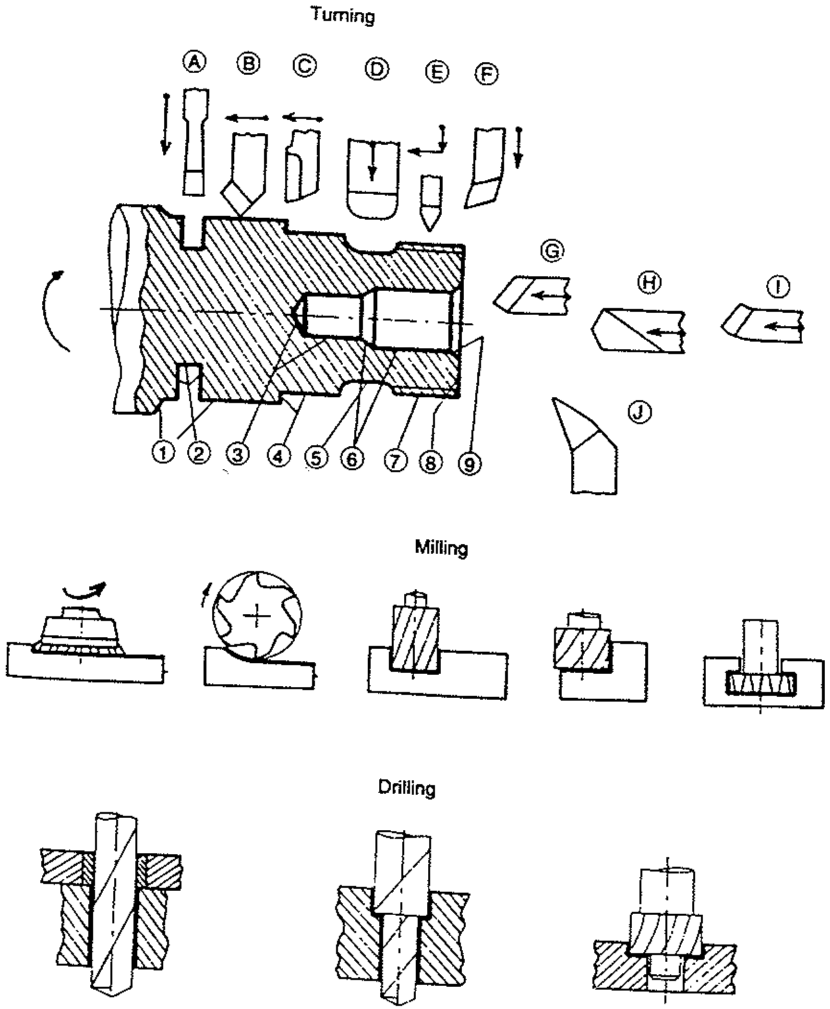


Fig. 5.9 Common metal removing processes.

1. *Milling* The tool, which has several cutting edges, rotates and the workpiece moves in one of several given directions, according to the shape required. For complex shapes (sculpture surfaces) three additional degrees of freedom are added. In Chapter 14, additional milling operations are described.
2. *Turning* The tool, usually with one cutting edge, moves in one x–z direction, while the part rotates around its line of symmetry. Therefore, only round symmetrical parts can be produced.

3. *Drilling* The tool rotates and moves in the z direction, while the workpiece can move in the x and y directions. In Chapter 13, additional hole-making processes such as reaming, boring and milling are described.
4. *Cylindrical grinding* The tool rotates and moves in the x–y direction, while the workpiece rotates. In surface grinding, the workpiece moves in the x–y direction while the tool rotates. Grinding is used to improve workpiece surface roughness. Processes for improving surface roughness further are honing and lapping. These two processes use abrasive rather than chipping tools for removing stock from the workpiece.

A laser process is illustrated in Fig. 5.10, and described below.

1. *Broaching* Used to produce non-round holes. The tool is composed of successive linear cutting edges, gradually increasing in size, where the final cutting edge has the desired hole shape. The tool is moved in one direction while the workpiece is stationary. Each shape must have its own special tool, which can be expensive.
2. *EDM* Electrodischarge machining (and ECM, electrochemical machining) are non-conventional processes. The tool has the shape of the required workpiece and moves in the z direction. The workpiece is stationary. Sparks vaporize a small spot on the workpiece material which is then washed away by an electrolyte. This method is effective for machining very hard material and producing odd shapes with high surface finish.
3. *Laser beam machining* A process using a light beam of high intensity and single frequency to burn and vaporize workpiece material.

The machines employed are usually universal machines that use universal and commercial tools. Tight dimensional tolerances and good surface finishes can be maintained, without changing material properties during manufacture. This material removal process is best suited for small quantities. However, with special tools, jigs and fixtures, automated versions of machine tools, numerically controlled machines and transfer lines, the process may be adapted to large quantity, mass production manufacturing.

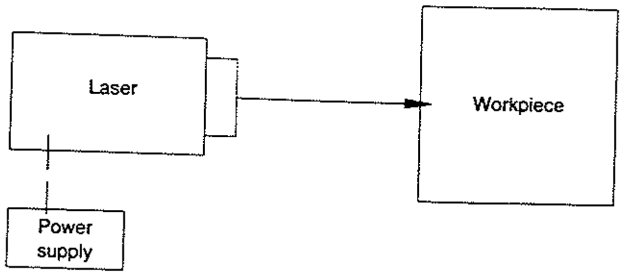


Fig. 5.10 Laser use in metal removal processes.

5.2.4 Forming by joining parts

This technique involves the use of welding, brazing, soldering and adhesive to join several components into one complex part. It is often used in conjunction with the material removal process to eliminate excessive waste of raw material.

Welding results in a strong bond between components; however, since it is a high temperature process, with the material being heated to melting point, distortions, shrinkage and chemical changes may occur, therefore not all materials are suitable for welding. If tight dimensional tolerances and a good surface finish are required, additional processes should be applied.

Good weld joints will have at least the same strength as the components themselves. Design for welding may use relatively thin walled materials, with ribs to strengthen the part. Industrial robots may be used to perform this operation.

Soldering and brazing produce a weaker joint than welding. They use filler materials whose melting points are lower than those of the component materials, although both can produce a wide range of material combinations.

Adhesives can be used to join different types of materials; for example, metal to wood, plastic to metal, plastic to plastic. A strong joint with no distortion or shrinkage can be obtained. Rubber based adhesives produce elastic and vibration-resistant joints. Special surface treatment is required, and the designer must realize that the strength of the joint is not uniform in all directions (usually, the joint is strong in shear and weak in peeling).

5.2.5 Forming by assembly

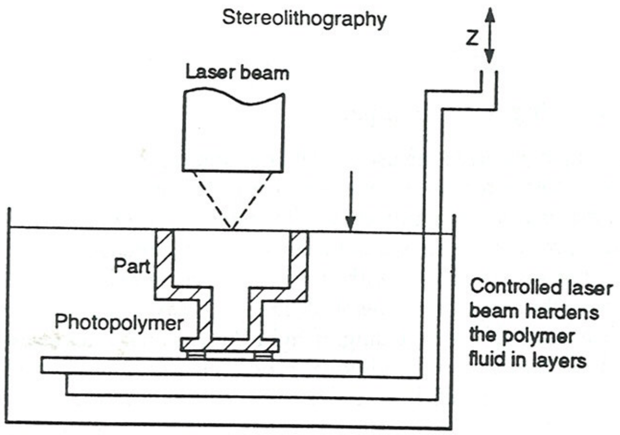
This technique involves the mechanical joining of parts by threads, bolts, rivets, assembly by press, etc.

5.2.6 Forming by material increase (incress)

This is a new technique applying a kind of selective solidification or binding of liquid or solid particles by glueing, welding, polymerization or chemical reaction. Material is progressively added until the whole part is created.

Most techniques build up parts in successive two-dimensional layers created one on top of the other. This is done by slicing a CAD model of the part to reveal horizontal layers, usually a few tenths of a millimeter deep. A single layer is created by scanning and solidifying it in a point-to-point fashion by means of a laser beam.

There are several methods of solidifying the layer. Figure 5.11 shows the stereolithography method. The main advantage of this technique is that parts can be produced directly from a CAD system with no extra tooling or dies. As it is a slow and expensive process, it is used mostly to build prototypes and one-of-a-kind parts. This process is also called **rapid prototyping**.



Model grower cycle (with UV light):

1. Spread thin layer of photopolymer.
2. Expose the layer to UV light to instantly cure all exposed areas.
3. Wipe and collect residual unsolidified material.
4. Wax fill all cavities.
5. Cool the wax.
6. Mill the layer to its exact thickness.

Mask generation is performed in tandem with layer processing. Everything is done within one integrated machine.

Fig. 5.11 Rapid prototyping.

5.3 DESIGN FOR MANUFACTURING

A part can often be manufactured by any of the available processes. However, the part shape and dimensions will be different according to the process selected.

For example, a machine frame can be cast or constructed from profile bars that are welded, riveted or bolted. The stress and strain computations are different in each case. The strength constraint is not always the controlling one; it is possible that the selected process capabilities will control the design. Figure 5.12 illustrates examples of design for manufacturing. Some general considerations are applicable as a function of the process:

(a) *Casting or molding* The thickness of the fin and the adjoining fillets have to be large in order to allow material flow in the die. The thickness will probably be determined by process rather than strength considerations.

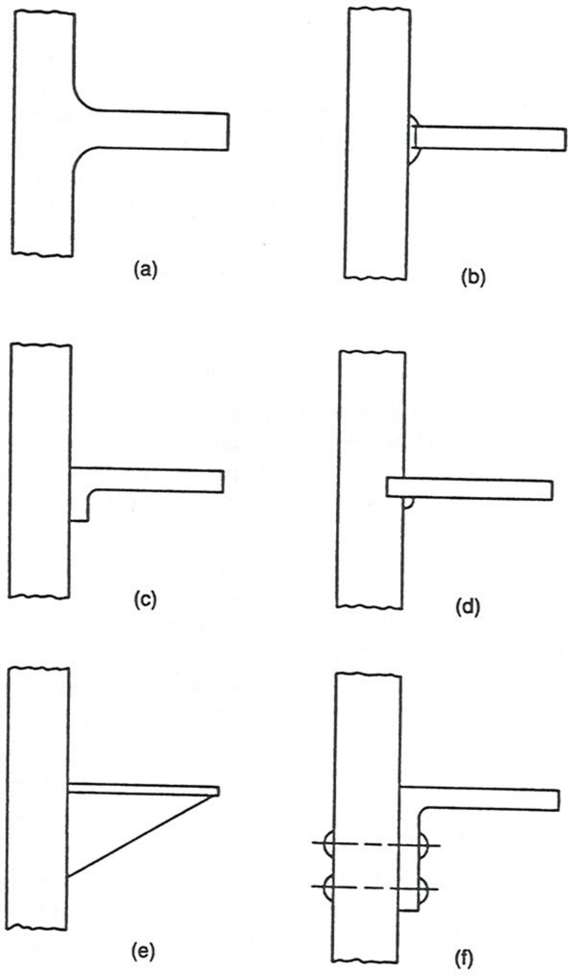


Fig. 5.12 Examples of design for manufacturing.

(b) *Welded joints* The thickness of the part may be controlled by strength constraints and will probably be significantly smaller than that in casting. There is a minimum thickness required for welding, but it is much less than in casting or molding. The design problem lies in the joint itself. Butt welding is weak in this case, and in order to increase welding strength and ease of part positioning, a bend of the fin (c) or slot (d) in the body is recommended.

(e) *Welded joint with support plate* For added strength and reduced fin thickness, support plates can be used.

(f) *Riveted joint* The fin must have a 'T' or 'L' shape in order to leave room for the rivets. The thickness can be controlled by the strength constraint and the shape and size by assembly constraints. A sharp corner at the top of the fin may result. The length of the bend depends on the number of rivets required to resist the load. *Bolted joint* The considerations used for rivets also apply in this case, with the provision that sufficient space be available for a thread in the body and a wrench. If the body is thin, either a screw and nut or self-tapping screws can be used, depending on body thickness and accessibility for a wrench or screwdriver.

In machine–metal removal, the thickness of the fin will probably be determined by strength consideration rather than process considerations. The adjoining fillets have to be small in order to save machining time.

Any one of the above design alternatives will meet product specifications. Costs, manufacturing time and facilities required for any one of the above alternatives will, however, vary.

The decision as to which method to select is the product designer's. He is neither a process planner, nor an economist, yet his decision constrains the process planner. It should be remembered that if the process the designer had in mind is not the one selected by process planning, a review of part design should be made.

CE (concurrent engineering) proposes that the decision should be mutual and should be taken after discussions between all disciplines involved in or affected by the decision. A good design for manufacturing should strike a balance between material cost, manufacturing cost and assembly cost.

5.4 SELECTING PRIMARY MANUFACTURING PROCESSES – ROUGH RULES

The following design factors have a bearing on the choice of a manufacturing process:

1. Quantity.
2. Complexity of form.
3. Nature of material.
4. Size of part.
5. Section thickness.
6. Dimensional accuracy.
7. Cost of raw material, possibility of defects and scrap rate.
8. Subsequent processes.

The choice of process should be made initially with economic factors in mind. The differences in direct manufacturing time can be quite significant. For example, the direct time taken to mold a part of moderate complexity with a metal die is about 25 seconds; to produce the same part using a material removal process might take about an hour. However, the cost of the metal die is high, probably in the neighborhood of $25,000. Assuming that the direct labor cost of the material removal process is about $15 per hour (ignoring indirect hourly rate and set-up costs, which will probably be higher for the molding process) the economic quantity should be at least $25{,}000/15 = 1666$ pieces in order to reach break-even point.

The quantity required will be a major determining factor of process selection. As was shown in Chapter 1, thinking time should be restricted to an economic level. Therefore, rules of thumb are needed.

As a general rule, the manufacturing processes may be ranked in order of economic consideration as follows:

High quantity (2000 or more)

1. Forming from solid by deformation
2. Forming from liquid – casting, molding
3. Forming by joining parts
4. Forming from solid by material removal
5. Forming by assembly

NB Forming by material increase is not suitable.

Low quantity (up to 50)

1. Forming from solid by material removal
2. Forming by joining parts
3. Forming from solid by deformation
4. Forming by assembly
5. Forming by material increase

NB Forming from liquid – casting, molding – is not suitable.

Medium quantities should be analyzed separately in each case. However, in order to save thinking and computation time, additional rules may be added relating to quantity and part complexity:

For a simple part, the lower quantity should be increased to 150 pieces and the higher quantity should be reduced to 1000 pieces. For complex parts, the higher quantity may be reduced to 1500 pieces.

A more specific ranking of primary process selection is given in the next section.

5.5 SELECTING PRIMARY MANUFACTURING PROCESSES – REFINED RULES IN RELATION TO THEIR CAPABILITY AND QUANTITY

Selecting the primary manufacturing forming process should be the first decision. Then, to check which process is most suitable for manufacturing the required part, refined rules are considered.