CHAPTER 50

Design for Manufacturing*

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1. INTRODUCTION

The objective of design for manufacturability is to incorporate producibility issues early on in the product design stage so that the customers can be attracted and the needs of the customers can be satisfied in a short lead time and at a competitive cost. The customers' needs include satisfaction in the product with respect to its performance capabilities, quality, reliability, serviceability, aesthetics, and time of delivery.

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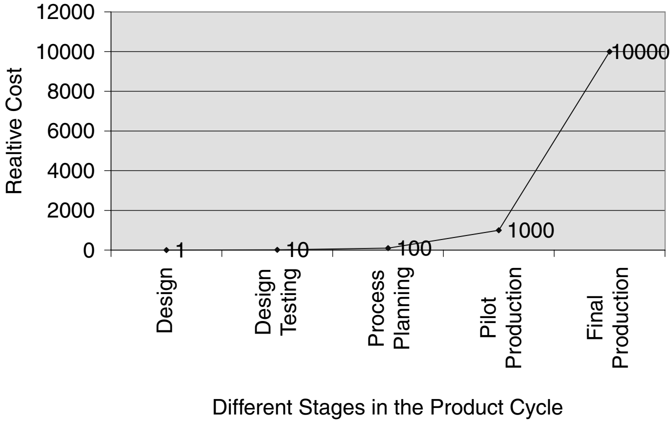


Figure 1 Comparative Cost of an Engineering Change in Different Stages in the Product Cycle. (*Source:* Shina 1991)

Conventional engineering practice in the past has resulted in separate, and sometimes isolated, activities between design and manufacturing that have proven to be time consuming and costly. A study compared the cost of any change in design in three different stages, namely, in production, manufacturing engineering, and design. The cost of a change in the production stage may be ap-

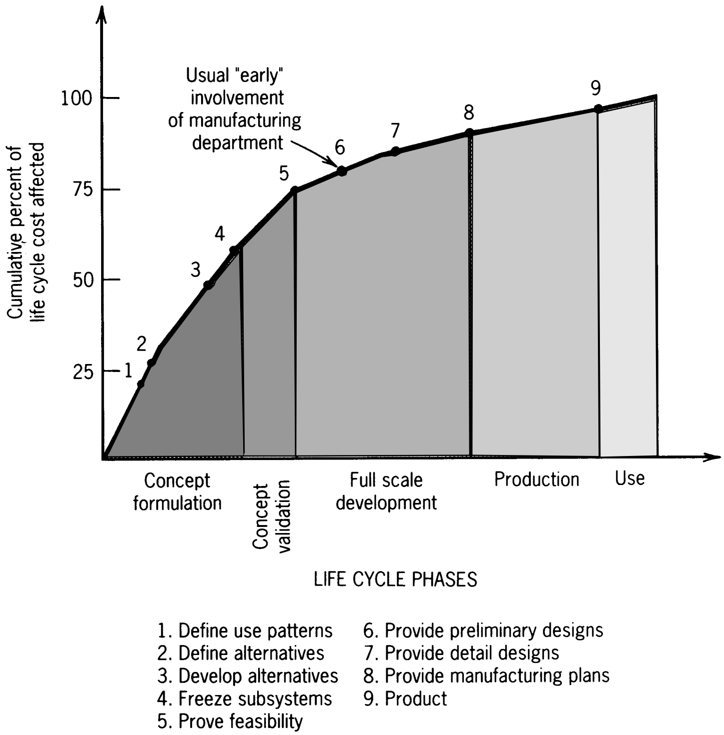


Figure 2 Life-Cycle Phases.

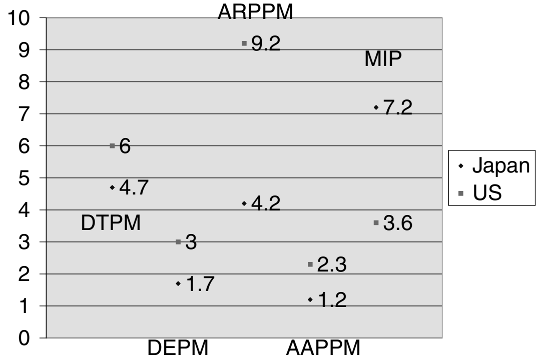


Figure 3 Comparison between Japanese and U.S. auto industry. DTPM: design time/model (multiply the number by 10 to convert the time unit into month); DEPM: design effort/model; ARPPM: average replacement period/model (years); AAPPM: average annual production/model (multiple the number by 100,000); and MIP: models in production (multiple the number by 10). (*Source:* Shina 1991).

proximately an order of magnitude more than the cost of the change made early in the manufacturing engineering stage. Figure 1 shows comparative cost of an engineering change in different stages in the product cycle. To avoid the costly changes due to manufacturability problems, factors related to manufacturing must be considered in all phases of the design process, starting with the design-conception phase. Another study (Nevins and Whitney 1989) further confirmed the importance of making the right decision early. This study indicated that in the concept formulation stage 60% of the life-cycle cost of a product has already been determined. Before full-scale development 75% of the life-cycle cost has been determined. This is illustrated in Figure 2. It is clear from the figure that the DFM needs to be considered in the early conceptual design stage to yield the maximized benefits.

The major issues in competitiveness have moved from cost to productivity to quality. The current and future major issue is time. The other issue are not less important, but the new frontier is speed: studies have shown that over 80% of market share in a new product category goes to the first two companies that get their products to market. Further studies have shown that a 20% cost overrun in the design stage of the product cycle will result in about 8% reduced profits over the lifetime of the product. A six-month overrun in time during the design stage today will result in about 34% loss over the life of the product (Brazier and Leonard 1990).

Figure 3 compares Japanese and U.S. auto design and product cycles. The competitive advantage of the Japanese auto industry results from concurrent engineering and design for manufacture (Shina 1991).

2. DESIGN AND DESIGN ALTERNATIVES

The essence of design is that it is a plan to achieve a purpose or to satisfy a need. In mechanical design, the plan is a representation, such as a set of drawings defining the configuration (geometry and material) of physical elements.

The immediate purpose of a specific set of physical elements or a specific design is the functional requirement. The design process, at this level, is to start with the known functional requirement to plan or search for the design configurations.

The design solution is almost always not unique. Conceptually, the design process can be considered a mapping process between the "purpose space" and the "functional space" and between the "functional space" and "configuration space." The ability to develop alternative physical designs is of fundamental importance to design for manufacturability.

Alternative physical designs may be developed by knowing the functional requirement. A design, in general, can be decomposed into subfunctional requirements for each of its subsystems. Each subfunctional requirement, again, can be used to characterize and develop the design alternatives of each subsystem. By repeating this process, a functional design hierarchy can be developed with the possible design alternatives at various levels of functional requirements, for the product (the assembly), the subassembly, and parts. This design hierarchy is shown in Figure 4 (Liu and Trappey 1989).

The properties of the design hierarchy are as follows:

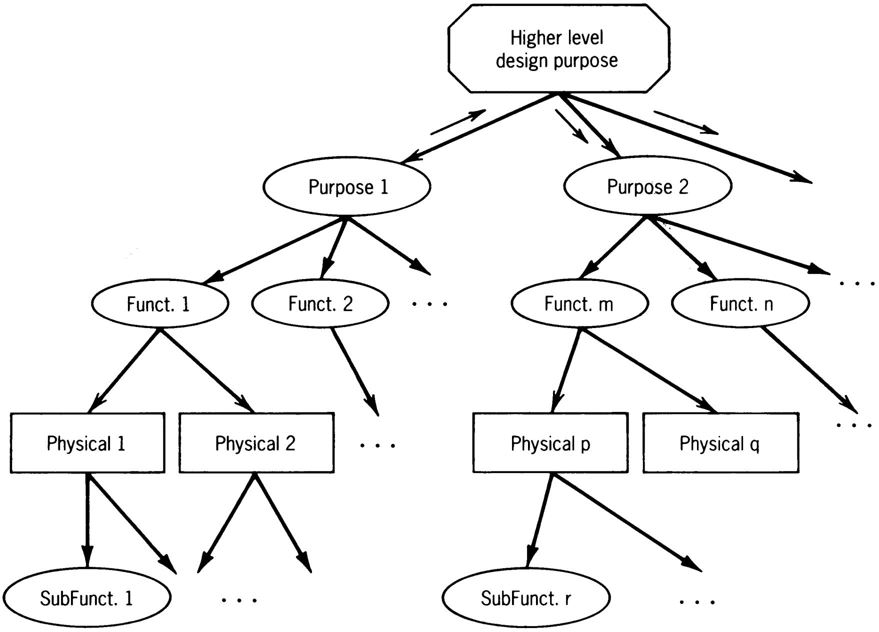


Figure 4 The Design Hierarchy with Upstream and Downstream Reasonings.

1. All the subfunctions are required to form a design, and only one among all the physical design alternatives is needed to satisfy a specific functional requirement.
2. Each and every possible physical design, for a system or a subsystem, has place in the hierarchy. Therefore, the hierarchy serves as a guide for design knowledge acquisition, as a structure for design knowledge storage, and as an indexing system for design knowledge retrieval. This has important application in serving as a software tool for concurrent engineering.
3. Upstream reasoning from the physical design can be conducted by answering the question "What is the design for?" Then the higher level functional requirement may be reached.
4. Downstream reasoning from functional requirement can be done by answering the question "How can the functional requirement be satisfied?" Then the physical design alternatives may be generated.
5. Upstream–downstream reasoning forces the designer to analyze the functional requirements and higher purposes. Thus, it can be used for managing the design process and yet, in the meantime, allow for the individual designer's creativity (see Figure 2).
6. The hierarchical system can serve as structured blackboard for design communication, consultation, and retrieval.

The application of the design hierarchy by one of the authors (Liu) has led to very significant product innovation. When the same method was applied by the students in his classes, general improvement in design creativity was observed. However, the results varied tremendously among the individuals.

More discussions and elaboration of the proposed functional–physical design hierarchy were done in Liu and Trappey (1989) and Trappey and Liu (1990).

3. DRAWINGS

Drawings represent the heart of design for manufacturing because they are the principal means of communication between the functional designer and the producer of the design. They alone control and completely delineate shape, form, fit, finish, and interchangeability requirements that lead to the most competitive procurement. An engineering drawing, when supplemented by reference specifications and standards, should permit a competent manufacturer to produce the part shown within the dimensional and surface tolerance specifications provided. It is the engineering drawing that should demonstrate the most creative design for manufacturing thinking.

Certain product specifications may not be included on the drawings in view of space constraints. Product specifications such as quality assurance checkpoints, inspection procedures, and general design criteria may be separately summarized but should always be cross-referenced on the engineering drawing. At all times the design engineer must remember that the end product drawing is the communication medium between the design engineer and the producer. It is the basis for interchangeability for repair parts; it provides the form, fit, and function to the manufacturing function.

Too often the language of drawings is incomplete. For example, chamfers may be indicated but not be dimensioned; worse yet, they may be desired but not even be shown. Frequently the finish desired is omitted. Complex coring may be incorrectly shown. The principal errors common to many designs are as follows:

1. Design is not conducive to the application of economic processing.
2. Designer has not taken advantage of group technology and creates a new design for an already existing item.
3. Design exceeds the manufacturing state of the art.
4. Design and performance specifications are not compatible.
5. Critical location surfaces have not been established.
6. Design specifies the use of inappropriate items.
7. Design specifications are not definitive.
8. Inadequate consideration has been given to measurement problems.
9. Tolerances are more restrictive than necessary.
10. Item has been overdesigned.

4. GENERAL PRINCIPLES FOR DESIGN FOR MANUFACTURABILITY

In this section we only stress some important concepts. In later sections we will review the design for basic processes. For more detailed information, see Bralla (1986) and Stillwell (1989).

1. Consider the entire product, including all its subsystems and components, and the entire spectrum of manufacturing–inspection–assembly activities. We should avoid producing improvement in one at the expense of another. For example, product design to specify the assembly operations may create difficulties in disassembling the product, thus hurting maintainability and serviceability of the product. Simplifying the component processing may create complexity in assembly.
2. Search for simplicity first in system designs, then in subsystem designs, and then in component designs. Considering simplicity in component level only will lead to missing the opportunities for significant improvement.
3. Ask whether the functional needs are absolutely necessary. Chances are the functional needs can be reduced, thus leading to significant simplifications of the configuration design and processing requirements. Example: A careful examination of the functional needs of a gear train system has led to a relaxation of the functional specifications that enables the use of a four-bar linkage as a replacement of the gear train. The impact on manufacturability is obviously very significant.

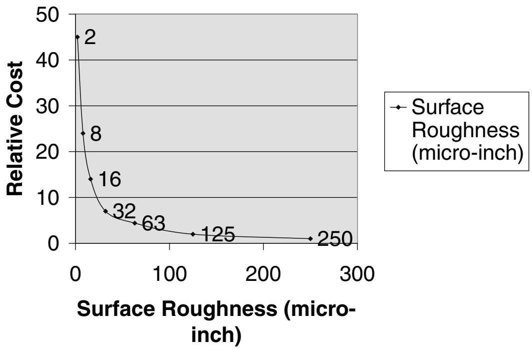


Figure 5 Relative Cost Corresponding to Different Surface Roughness. (*Source:* Bralla 1986)

4. Design for fewer parts, simpler shapes, least precision requirements, fewer manufacturing steps, and minimum information requirements. Figure 5 shows the relative cost corresponding to different surface roughness.
5. Apply the concept of design modularization and group technology. Reduce the varieties of sizes and shapes. Experience has shown that the number of hole sizes may be reduced significantly without affecting the function, thus reducing the number of sizes of drills needed.
6. Always consider standard materials, components, and subassemblies.
7. Design appropriate to the expected level of production and to fit the existing production facilities.
8. Select the shape of the raw material close to the finished designs.
9. Design for easy inspection.
10. Design for part orientation to maximize the value added in each setup.
11. Design for easy assembly and maintainability.

5. PROCESSES AND MATERIALS FOR PRODUCING THE DESIGN

The selection of the ideal processes and materials with which to produce a given design cannot be an independent activity. It must be a continuing activity that takes place throughout the design life cycle, from initial conception to production. Material selection and process selection need to be considered together; they should not be considered independently.

In considering the selection of materials for an application, it is usually possible to rule out entire classes of materials because of cost or their obvious inability to satisfy specific operational requirements. But even so, with the acceleration of material development there are so many options for the functional design engineer that optimum selection is at best difficult. The suggested procedure for organizing data related to material selection is to divide it into three categories: properties, specifications, and data for ordering.

The property category will usually provide the information that suggests the most desirable material. A property profile is recommended, where all information, such as yield point, modulus of elasticity, resistance to corrosion, and so on, is tabulated. Those materials that qualify because of their properties will stand out.

Each material will have its own specifications on the individual grades available and on their properties, applications, and comparative costs. The unique specifications of a material will distinguish it from all competing materials and will serve as the basis for quality control, planning, and inspection.

Finally, the data needed when physically placing an order need to be maintained. This includes minimum order size, quantity breakpoints, and sources of supply.

In the final selection of a material, cost of the proposed material needs to be considered—hence the need for close association between material selection and process selection in connection with design.

Design evaluation invariably is in terms of a proposed material cost, which may be derived by analyzing the involved processing steps, including setup and lead-time costs along with the preprocessed material cost.

6. DESIGN FOR BASIC PROCESSES—METAL

6.1. Liquid State

Early in the planning of the functional design, one must decide whether to start with a basic process that uses material in the liquid state, such as a casting, or in the solid state, such as a forging. If the engineer decides a part should be cast, he or she will have to decide simultaneously which casting alloy and process can most nearly meet the required dimensional tolerance, mechanical properties, and production rate at the least cost.

Casting has several distinct assets: the ability to fill a complex shape, economy when a number of similar pieces are required, and a wide choice of alloys suitable for use in highly stressed parts, where light weight is important or where corrosion may be a problem. There are inherent problems, too, including internal porosity, dimensional variations caused by shrinkage, and solid or gaseous inclusions stemming from the molding operation. However, most of these problems can be minimized by sound design for manufacturing.

Casting processes are basically similar in that the metal being formed is in a liquid or highly viscous state and is poured or injected into a cavity of a desired shape.

The following design guidelines will prove helpful in reducing casting defects, improving their reliability and assisting in their producibility:

1. When changes in sections are required, use smoothly tapered sections to reduce stress concentration. Where sections join, use generous fillets and blending radii.
2. Machining allowances should be detailed on the part drawing so as to ensure adequate stock and avoid excessive differences in casting thickness.
3. Remember that when design castings to be produced in a metal mold or die, convex forms are easy to mill but concave notches are both difficult and expensive.
4. Raised lettering is simple to cut into a metal mold or die; depressed lettering will cost considerably more.
5. Avoid the design of thin sections since they will be difficult to fill.
6. To facilitate the secondary operations of drilling and tapping, cored-through holes should have countersinking on both ends of the holes.
7. Avoid large, plain surfaces. Break up these areas with ribs or serration to avoid warpage and distortion.
8. For maximum strength, keep material away from the neutral axis. Endeavor to keep plates in tension and ribs in compression.

Table 1 identifies the important design parameters associated with the various casting processes and provides those limitations that should be incorporated by the functional designer to ensure producibility.

6.2. Solid State

A forging, as opposed to a casting, is usually used because of improved mechanical properties, which are a result of working metals into a desired configuration under impact or pressure loading. A refinement of the grain structure is another characteristic of the forging process. Hot forging breaks up the large dendritic grain structure characteristic of castings and gives the metal a refined structure, with all inclusions stretched out in the direction in which plastic flow occurs. A metal has greater load-carrying ability in the direction of its flow lines than it does across the flow lines. Consequently, a hot-formed part should be designed so that the flow lines run in the direction of the greatest load during service.

An extension of conventional forging known as precision forging can be used to acquire geometric configurations very close to the final desired shape, thus minimizing secondary machining operations.

Guidelines that should be observed in the design of forging in order to simplify its manufacturing and help ensure its reliability are as follows:

1. The maximum length of bar that can be upset in a single stroke is limited by possible buckling of the unsupported portion. The unsupported length should not be longer than three times the diameter of the bar or distance across the flats.
2. Recesses in depth up to their diameter can be easily incorporated in either or both sides of a section. Secondary piercing operations to remove the residual web should be utilized on through-hole designs.
3. Draft angle should be added to all surfaces perpendicular to the forging plane so as to permit easy removal of the forged part. Remember that outside draft angles can be smaller than inside angles since the outside surfaces will shrink away from the die walls and the inside surfaces will shrink toward bosses in the die.
4. Deeper die cavities require more draft than shallow cavities. Draft angles for hard-to-forge materials, such as titanium and nickel-base alloys, should be larger than when forging easy-to-forge materials.
5. Uniform draft results in lower-cost dies, so endeavor to specify one uniform draft on all outside surfaces and one larger draft on all inside surfaces.
6. Corner and fillet radii should be as large as possible to facilitate metal flow and minimize die wear. Usually 6 mm (0.24 in.) is the minimum radius for parts forged from high-temperature alloys, stainless steels, and titanium alloys.
7. Endeavor to keep the parting line in one plane since this will result in simpler and lower-cost dies.
8. Locate the parting lines along a central element of the part. This practice avoids deep impressions, reduces die wear, and helps ensure easy removal of the forged part from the dies.

Table 2 provides important design for manufacturing information for the major forging processes.

TABLE 1 Important Design Parameters Associated with Various Casting Processes

Design Parameter	Casting Process							
	Sand Casting							
	Green	Dry/Cold/Set	Shell	Plaster (Preheated Mold)	Investment (Preheated Mold)	Premanent Mold (Preheated Mold)	Die (Preheated Mold)	Centrifugal
Weight	100 g to 400 MT	100 g to 400 MT	100 g to 100 kg	100 g to 100 kg	Less than 1 g to 50 kg	100 g to 25 kg	Less than 1 g to 30 kg	Grams to 200 kg
Minimum section thickness	3 mm	3 mm	1.5 mm	1 mm	0.5 mm	3 mm	0.75 mm	6 mm
Allowance for machining	Ferrous—2.5–9.5 mm; nonferrous—1.5–6.5	Ferrous—2.5–9.5 mm; nonferrous—1.5–6.5 mm	Often not required; when required, 2.5–6.5 mm	0.75 mm	0.25–0.75 mm	0.80–3 mm	0.80–1.60 mm	2.50–6.5 mm
General tolerance	$\pm0.4 \sim 6.4$ mm	$\pm0.4 \sim 6.4$ mm	$\pm0.08 \sim \pm1.60$ mm	$\pm0.13 \sim \pm0.26$ mm	±0.05–±1.5 mm	±0.25–±1.5 mm	±0.025–±0.125 mm	±0.80–±3.5 mm
Surface finish (μrms)	6.0–24.0	6.0–24.0	1.25–6.35	0.8–1.3	0.5–2.2	2.5–6.35	0.8–2.25	2.5–13.0
Process reliability	90	90	90	90	90	90	90	90
Cored holes	Holes < 6 mm	Holes < 6 mm	Holes < 6 mm	Holes < 12 mm	Holes as small as 0.5 mm diameter	Holes as small as 5 mm diameter	Holes as small as 0.80 mm diameter	Holes as small 25 mm diameter; no undercuts
Minimum lot size	1	1	100	1	20	1000	3000	100
Draft allowances	1°–3°	1°–3°	$\frac{1}{4}$°–1°	$\frac{1}{2}$°–2°	0°–$\frac{1}{2}$°	2°–3°	2°–5°	0°–3°

TABLE 2 Important Design Parameters Associated with Various Forging Processes

Design Parameter	Forging Process				
	Open Die	Conventional Utilizing Preblocked	Closed Die	Upset	Precision Die
Size or weight	500 g to 5000 kg	Grams to 20 kg	Grams to 20 kg	20–250 mm bar	Grams to 20 kg
Allowance for finish machining	2–10 mm	2–10 mm	1–5 mm	5–10 mm	0–3 mm
Thickness tolerance	±0.6 mm −0.2 mm to +3.00 mm −1.00 mm	+0.4 mm −0.2 mm to +2.00 mm −0.75 mm	+0.3 mm −0.15 mm to +1.5 mm − 0.5 mm	—	+0.2 mm −0.1 mm to +1 mm 0.2 mm
Filet and corners	5–7 mm	3–5 mm	2–4 mm	—	1–2 mm
Surface finish (μrms)	3.9–4.5	3.8–4.5	3.2–3.8	4.5–5.0	1.25–2.25
Process reliability	95	95	95	95	95
Minimum lot size	25	1000	1500	25	2000
Draft allowance	5°–10°	3°–5°	2°–5°	—	0°–3°
Die wear tolerance	±0.075 mm/kg weight of forging	±0.075 mm/kg weight of forging	±0.075 mm/kg weight of forging		±0.075 mm/kg weight of forging
Mismathcing tolerance	±.25 mm ±0.01 mm/3 kg weight of forging	±0.25 mm ±0.01 mm/3 kg weight of forging	±0.25 mm ±0.01 mm/3 kg weight of forging	—	±0.25 mm ±0.01 mm/3 kg weight of forging
Shrinkage tolerance	±0.08 mm	±0.08 mm	±0.08 mm	—	±0.08 mm

6.3. Other Basic Processes

In addition to casting and forging, several other processes that may be considered basic since they impart the approximate finished geometry to material that is in the powdered, sheet, or rod-shape form. Notable among these are powder metallurgy, cold heading, extrusion, roll forming, press forming, spinning, electroforming, and automatic screw machine work.

In powdered metallurgy, powdered metal is placed in a die and compressed under high pressure. The resulting cold-formed part is then sintered in a furnace to a point below the melting point of its major constituent.

Cold heading involves striking a segment of cold material up to 25 mm (1 in.) in diameter in a die so that it plastically deformed to the die configuration.

Extrusion is performed by forcing heated metal through a die having an aperture of the desired shape. The extruded lengths are then cut into the desired length. From the standpoint of producibility, the following design features should be observed:

1. Very thin sections with large circumscribing area should be avoided.
2. Any thick wedge section that tapers to a thin edge should be avoided.
3. Thin sections that have close space tolerance should be avoided.
4. Sharp corners should be avoided.
5. Semiclosed shapes that necessitate dies with long, thin projections should be avoided.
6. When a thin member is attached to a heavy section, the length of the thin member should not exceed 10 times its thickness.

In roll forming, strip metal is permanently deformed by stretching it beyond its yield point. The series of rolls progressively changes the shape of the metal to the desired shape. In design, the extent of the bends in the rolls, allowance must be made for springback.

In press forming, as in roll forming, metal is stretched beyond its yield point. The original material remains about the same thickness or diameter, although it will be reduced slightly by drawing or ironing. Forming is based upon two principles:

1. Stretching and compressing material beyond the elastic limit on the outside and inside of a bend.
2. Stretching the material beyond the elastic limit without compressing the material beyond the elastic limit without stretching.

Spinning is a metal-forming process in which the work is formed over a pattern, usually made of hard wood or metal. As the mold and material are spun, a tool (resting on a steady rest) is forced against the material until the material contacts the mold. Only symmetrical shapes can be spun. The manufacturing engineer associated with this process is concerned primarily with blank development and proper feed pressure.

In electroforming, a mandrel having the desired inside geometry of the part is placed in an electroplating bath. After the desired thickness of the part is achieved, the mandrel pattern is removed, leaving the formed piece.

Automatic screw machine forming involves the use of bar stock, which is fed and cut to the desired shape.

Table 3 provides important design for manufacturing information for these basic processes.

7. DESIGN FOR SECONDARY OPERATION

Just as there should be careful analysis in the selection of the ideal basic or primary process, so must there be sound planning in the specification of the secondary processes. The parameters associated with all process planning include the size of the part, the geometric configuration or shape required, the material, the tolerance and surface finished needed, the quantity to be produced, and of course the cost. Just as there are several alternatives in the selection of a basic process, so there are several alternatives in determining how a final configuration can be achieved.

With reference to secondary removal operations, several guidelines should be observed in connection with the design of the product in order to help ensure its producibility.

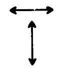
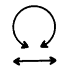
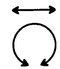
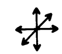
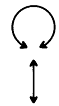
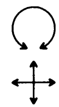
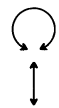
1. Provide flat surfaces for entering of the drill on all holes that need to be drilled.
2. On long rods, design mating members so that male threads can be machined between centers, as opposed to female threads, where it would be difficult to support the work.
3. Always design so that gripping surfaces are provided for holding the work while machining is performed and ensure that the held piece is sufficiently rigid to withstand machining forces.
4. Avoid double fits in design for mating parts. It is much easier to maintain close tolerance when a single fit is specified.
5. Avoid specifying contours that require special form tools.
6. In metal stamping, avoid feather edges when shearing. Internal edges should be rounded, and corners along the edge of the strip stock should be sharp.
7. In metal stamping of parts that are to be subsequently press formed, straight edges should be specified, if possible, on the flat blanks.
8. In tapped blind holes, the last thread should be at least 1.5 times the thread pitch from the bottom of the hole.
9. Blind-drilled holes should end with a conical geometry to allow the use of standard drills.
10. Design the work so that diameters of external features increase from the exposed face and diameters of internal features decrease.
11. Internal corners should indicate a radius equal to the cutting tool radius.
12. Endeavor to simplify the design so that all secondary operations can be performed on one machine.
13. Design the work so that all secondary operations can be performed while holding the work in a single fixture or jig.

Table 4 provides a comparison of the basic machining operations used in performing the majority of secondary operations.

TABLE 3 Important Design Parameters Associated with Manufacturing Information for Basic Processes

Design Parmeter	Powder Metallurgy	Cold Headng	Extrusion	Roll Forming	Press Forming	Spinning	Electroforming	Automatic Screw Machine
Size	Diameter—1.5–300 mm; length—3–225 mm	Diameter—0.75–20 mm; length—1.50–250 mm	1.5–250 mm diameter	1–2000 mm	Up to 6 mm diameter	6–4000 mm	Limited to size of plating tanks	0.80 mm diameter by 1.50 mm; length to 200 mm diameter by 900 mm length
Minimun thickness	1 mm	—	1 mm	0.075 mm	0.075 mm	0.1 mm	0.0025 mm	—
Allowance for finish maching	To size	To size	To size	To size	To size	To size	To size	To size
Tolerance	Diameter—±0.025–0.125 mm; length—±0.25–0.50 mm	Diameter—−0.05–0.125 mm; length—±0.75–2.25 mm	Flatness—±0.01 mm/in. of width; wall thickness—±0.15–0.25 mm; cross section—±0.15–0.20	Cross section—±0.050–0.35 mm; length—±1.5 mm	±0.25 mm	Length—±0.12 mm; thickness—±0.05 mm	Wall thicknesses—±0.025 mm; dimension—±0.005 mm	Diameter—±0.01–.06 mm; length—±0.04–0.01 mm; 0.10 concentricity—±0.06 mm
Surface finish (μrms)	0.125–1.25	2.2–2.6	2.5–3	2.2–2.6	2.2–4.0	0.4–2.2	0.125–0.250	0.30–2.5
Process reliability	95	99	99	99	99	90–95	99	98
Minimum lot size	1000	5000	500 ft	10,000 ft	1500	5	25	1000
Draft allowance	0	—	—	—	$0°–\frac{1}{4}°$	—	—	—
Bosses permitted	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes
Undercuts permitted	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Inserts permitted	Yes	No	No	No	No	No	No	No
Holes permitted	Yes	No	Yes	Yes	Yes	No	Yes	Yes

TABLE 4 Machining Operations Used in Performing Secondary Operation

Process	Shape Produced	Machine	Cutting Tool	Tolerance	Surface Finish (πrms)	Relative Motion: Tool	Relative Motion: Work
Turning (external)	Surface of revolution (cylindrical)	Lath, boring machine	Single point	±0.005–±0.025 mm	0.8–6.4		
Boring (external)	Cylindrical (enlarges holes)	Boring machine	Single point	±0.005–±0.025 mm	0.4–5.0		
Shaping and planing	Flat surface or slots	Shaper, planer	Single point	±0.025–±0.050 mm	0.8–6.4		
Milling (end, form, slab)	Flat and contoured surfaces and slots	Milling machine—horizontal, vertical, bed-type	Multiple points	±0.025–±0.050 mm	0.8–6.4		
Drilling	Cylindrical (originating holes (0.1–100 mm diameter)	Drill press	Twin-edge drill	±0.050–±0.100 mm	2.5–6.4		Fixed
Grinding (cylindrical surface, plunge)	Cylindrical, flat and formed	Griding machine—cylindrical, surface, thread	Multiple points	±0.0025–±0.0075 mm	0.2–3.2		
Reaming	Cylindrical (enlarging and improving finish of holes)	Drill press, turret lathe	Multiple points	±0.0125–±0.0500 mm	0.8–2.5		Fixed
Broaching	Cylindrical, flat, slots	Broaching machine, press	Multiple points	±0.005–±0.0150 mm	0.8–2.5		Fixed
Electric discharge machining	Variety of shapes depending on shape of electrode	Electric discharge machine	Single-point electrode	±0.050 mm	0.8–5.0		Fixed

Electrochemical machining	Variety of shapes; usually odd-shapped cavities of hard material	Electrochemical machine	Dissolution process	±0.050 mm	0.3–1.5	Andoic dissolution; tool is cathode	Workpiece is anode
Chemical machining	Variety of shapes; usually blanking of intricate shapes, printed circuit etching, or shallow cavities	Chemical machining machine	Chemical attack of exposed surfaces	±0.050 mm	0.6–1.8	Chemical attack of exposed surfaces	Fixed
Laser machining	Cylindrical holes as small as 5 μm	Laser beam machine	Single-wavelength beam of light	Holes are reproducible within ±3%	0.6–2.5	Fixed	Fixed
Ultrasonic machining	Same shape as tool	Machine equipped with magneto-strictive transducer, generator power supply	Shaped tool and abrasive powder	±0.025 mm	0.3–0.9	↕	Fixed
Electron beam machining	Cylindrical slots	Electron beam machine equipped with vacuum of 10^{-4} mm of mercury	High-velocity electrons focus on workpiece	±0.025 mm	0.6–1.8	↕	Fixed
Gear generating	Eccentric cams, ratchets, gears	Gear shaper	Single-point reciprocating	±0.013–±0.025 mm	1.8–3.8	↕ ↻	↻
Hobbing	Any form that regularly repeats itself on periphery of circular part	Hobbing machine	Multiple points	±0.013–±0.025 mm	1.8–3.8	↻	↻
Treplanning	Large through holes, circular grooves	Lathe-like machine	One or more single-point cutters revolving around a center	±0.13 mm	2.5–6.4	↻	↻

8. DESIGN FOR BASIC PROCESSES—PLASTICS

There are more than 30 distinct families of plastic, from which evolve thousands of types and formulations that are available to the functional designer. However, in the fabrication of plastics, either thermoplastic or thermosetting, only a limited number of basic processes are available. These processes include compression molding, transfer molding, injection molding, extrusion, casting, cold molding, thermoforming, calendering, rotational molding, and blow molding. The functional designer usually gives little thought to how the part will be made. He or she is usually concerned primarily with the specific gravity, hardness, water absorption, outdoor weathering, coefficient of linear thermal expansion, elongation, flexural modulus, izod impact, deflect temperature under load, and flexural yield, tensile, shear, and compressive strengths.

8.1. Compression Molding

In compression molding, an appropriate amount of plastic compound (usually in powder form) is introduced into a heated mold, which is subsequently closed under pressure. The molding material, either thermoplastic or thermosetting, is softened by the heat and formed into a continuous mass having the geometric configuration of the mold cavity. If the material is thermoplastic, hardening is accomplished by cooling the mold. If the material is thermosetting, further heating will result in the hardening of the material.

Compression molding offers the following desirable features:

1. Thin-walled parts (less than 1.5 mm) are readily molded with this process with little warpage or dimensional deviation.
2. There will be no gate markings, which is of particular importance on small parts.
3. Less shrinkage, and more uniform, is characteristic of this molding process.
4. It is especially economical for larger parts (those weighing more than 1 kg).
5. Initial costs are less since it usually costs less to design and make a compression mold than a transfer or injection mold.
6. Reinforcing fibers are not broken up as they are in closed-mold methods such as transfer and injection. Therefore, the fabricated parts under compression molding may be both stronger and tougher.

8.2. Transfer Molding

Under transfer molding, the mold is first closed. The plastic material is then conveyed into the mold cavity under pressure from an auxiliary chamber. The molding compound is placed in the hot auxiliary chamber and subsequently forced in a plastic state through an orifice into the mold cavities by pressure. The molded part and the residue (cull) are ejected upon opening the mold after the part has hardened. Under transfer molding, there is no flash to trim; only the runner needs to be removed.

8.3. Injection Molding

In injection molding, the raw material (pellets, grains, etc.) is placed into a hopper, called the barrel, above a heated cylinder. The material is metered into the barrel every cycle so as to replenish the system for what has been forced into the mold. Pressure up to 1750 kg/cm^2 forces the plastic molding compound through the heating cylinder and into the mold cavities. Although this process is used primarily for the molding of thermoplastic materials, it can also be used for thermosetting polymers. When molding thermosets, such as phenolic resins, low barrel temperatures should be used (65–120°C). Thermoplastic barrel temperatures are much higher, usually in the range of 175–315°C.

8.4. Extrusion

Like the extrusion of metals, the extrusion of plastics involves the continuous forming of a shape by forcing softened plastic material through a die orifice that has approximately the geometric profile of the cross-section of the work. The extruded form is subsequently hardened by cooling. With the continuous extrusion process, such products as rods, tubes, and shapes of uniform cross-section can be economically produced. Extrusion to obtain a sleeve of the correct proportion almost always precedes the basic process of blow molding.

8.5. Casting

Much like the casting of metals, the casting of plastics involves introducing plastic materials in the liquid form into a mold that has been shaped to contour of the piece to be formed. The material that is used for making the mold is often flexible, such as rubber latex. Molds may also be made of nonflexible materials such as plaster. Epoxies, phenolics, and polyesters are plastics that are frequently fabricated by the casting process.

8.6. Cold Molding

Cold molding takes place when thermosetting compounds are introduced into a room-temperature steel mold that is closed under pressure. The mold is subsequently opened, and the formed article is transferred to a heating oven, where it is baked until it becomes hard.

8.7. Thermoforming

Thermoforming is restricted to thermoplastic materials. Here sheets of the plastic material are heated and drawn over a mold contour so that the work takes the shape of the mold. Thermosetting may also be done by passing the stock between a sequence of rolls that produce the desired contour. Most thermoplastic materials become soft enough for thermoforming between 135 and 220°C. The plastic sheet that was obtained by calendering or extrusion can be brought to the correct thermoforming temperature by infrared radiant heat, electrical resistance heating, or ovens using gas or fuel oil.

8.8. Calendering

Calendering is the continuous production of a thin sheet by passing thermoplastic compounds between a series of heated rolls. The thickness of the sheet is determined by adjusting the distance between the rolls. After passing between the final set of rolls, the thin plastic sheet is cooled before being wound into large rolls for storage.

8.9. Blow Molding

In blow molding, a tube of molten plastic material, the parison, is extruded over an apparatus called the blow pipe and is then encased in a split mold. Air is injected into this hot section of extruded stock through the blow pipe. The stock is then blown outward, where it follows the contour of the mold. The part is then cooled, the mold opened, and the molded part ejected. In very heavy sections, carbon dioxide or liquid nitrogen may be used to hasten the cooling. This process is widely used in molding high- and low-density polyethylene, nylon, polyvinyl chloride (PVC), polypropylene, polystyrene, and polycarbonates.

8.10. Parameters Affecting the Selection of the Optimum Basic Process

Selecting the optimum basic process in the production of a given plastic design will have a significant bearing on the success of that design. The principal parameters that should be considered in the selection decision include the plastic material to be used, the geometry or configuration of the part, the quantity to be produced, and the cost.

If the functional designer cannot identify the exact plastic material that is to be used, he or she should be able to indicate whether a thermoplastic or thermosetting resin is being considered. This information alone will be most helpful. Certainly both thermoforming and blow molding are largely restricted to thermosetting resins, as is transfer molding. Injection molding is used primarily for producing large-volume thermoplastic moldings, and extrusion for large-volume thermoplastic continuous shapes.

Geometry or shape also has a major impact on process selection. Unless a part has a continuous cross-section, it would not be extruded; unless it were relatively thin walled and bottle shaped, it would not be blow molded. Again, calendering is restricted to flat sheet or strip designs, and the use of inserts is restricted to the molding processes.

The quantity to be produced also has a major role in the selection decision. Most designs can be made by simple compression molding, yet this method would not be economical if the quantity were large and material were suitable for injection molding.

The following design for manufacturing points apply to the processing of plastics:

1. Holes less than 1.5 mm diameter should not be molded but should be drilled after molding.
2. Depth of blind holes should be limited to twice their diameter.
3. Holes should be located perpendicular to the parting line to permit easy material removal from the mold.
4. Undercuts should be avoided in molded parts since they require either a split mold or a removable core section.
5. The section thickness between any two holes should be greater than 3 mm.
6. Boss heights should not be more than twice their diameter.
7. Bosses should be designed with at least a 5° taper on each side for easy withdrawal from the mold.
8. Bosses should be designed with radii at both the top and the base.
9. Ribs should be designed with at least a 2–5° taper on each side.

TABLE 5 Basic Processes Used to Fabricate Plastics and Their Principal Parameters

	Parameter								
Process	Shape Produced	Machine	Mold or Tool	Material	Typical Tolerance	Minimum Wall Thickness	Ribs	Draft	Inserts	Minimim Quantity Requirements
Calendering	Continuous sheet for film	Multiple-roll calender	None	Thermoplastic	0.05–0.200 mm depending on material		None	None	None	Low
Extrusion	Continuous form such as rods, tubes, filaments, and simple shapes	Extrusion press	Hardened steel die	Thermoplastic	0.01–0.30 mm depending on material		None	None	Possible to extrude over or around wire insert	Low (tooling is inexpensive)
Compression molding	Simple outlines and plain cross sections	Compression press	Hardened tool steel mold	Thermoplatic or thermosetting	0.04–0.25 mm depending on material	1.25			Yes	Low
Transfer molding	Complex geometrics possible	Transfer press	Hardened tool steel mold	Thermosetting	0.04–0.25 mm depending on material	1.5 mm	3°–5° taper; height $<$ 3 times wall thickness	$\frac{1}{2}$°–5°	Yes	High
Injection molding	Complex geometrics possible	Injection press	Hardened tool steel mold	Thermoplastic or thermosetting	0.04–0.25 mm depending on material	1.25 mm	2°–5° taper; height = $1\frac{1}{2}$ times wall thickness; width $\frac{1}{2}$ of wall thickness	$\frac{1}{4}$°–4°	Yes	High
Casting	Simple outlines and plain cross sections	None	Metal mold or expoxy mold	Thermosetting	0.10–0.50 mm depending on material	2.0 mm			Yes	Low to medium depending on mold
Cold molding	Simple outlines and plain cross sections	None	Mold of wood, plaster, or steel	Thermosetting	0.01–0.05 mm depending on material	2.0 mm			Yes	Low

Blow molding	Thin walled and bottle shaped	Pneumatic blow molding machine	Tool steel mold	Thermoplastic				No	High
Rotational molding	Full enclosures or semienclosures (hollow objects)	Rotomolding system	Cast aluminum or fabricated metal	Thermoplastic, limited thermosetting	0.03–0.60 mm	3.0 mm		No	Medium
Filament winding	Tubes, piping, tanks	Filament winding machine	Must have axis about which the filament can be wound	Sing-end continuous strand glass fiber and thermoplastic	0.20–0.50 mm	3.0 mm			Medium

10. Ribs should be designed with radii at both the top and the base.
11. Ribs should be designed at a height of 1.5 times the wall thickness. The rib width of the base should be half the wall thickness.
12. Outside edges at the parting line should be designed without a radius. Fillets should be specified at the base ribs and bosses and on corners and should be not less than 0.8 mm.
13. Inserts should be at right angles to the parting line and of a design that allows both ends to be supported in the mold.
14. A draft or taper of 1–2° should be specified on the vertical surfaces or walls parallel with the direction of mold pressure.
15. Cavity numbers should be engraved in the mold. The letters should be 2.4 mm high and 0.18 mm deep.
16. Threading below 8 mm diameter should be cut after molding.

Table 5 identifies the major parameters associated with basic processes used to fabricate thermoplastic and thermosetting resins.

9. DESIGN FOR ASSEMBLY

The goal of DFA is to ease the assembly of the product. Boothroyd et al. (1994) propose a method for DFA that involves two principal steps:

- Designing with as few parts as possible. This is accomplished by analyzing parts pairwise to determine whether the two parts can be created as a single piece rather than as an assembly.
- Estimating the costs of handling and assembling each part using the appropriate assembly process to generate costs figures to analyze the cost savings through DFA.
- In addition to the assembly cost reductions through DFA, there are reductions in part costs that are more significant. Other benefits of DFA include improved reliability and reduction in inventory and production control costs. Consequently, DFA should be applied regardless of the assembly cost and product volume.

10. COMPUTER SOFTWARE TOOLS: OBJECT-ORIENTED PROGRAMMING AND KNOWLEDGE-BASED SYSTEMS

Modern CAD/CAM systems and computer-aided processing planning systems for machining are well known and are very important for integrating design and manufacturing. However, more work is needed to develop them into tools for helping design for manufacturability. We need a software system that can be easily modulized, expanded, alternated in its structures and contents, and integrated partially or fully. The key technology is a recently developed style and structure of programming called object-oriented programming (OOP).

Object-oriented programming supports four unique object functions or properties:

1. *Abstraction:* Abstraction is done by the creation of a "class protocol description" that defines the properties of any object that is an instance of that class.
2. *Encapsulation:* An object encapsulates all the properties (data and messages) of the specific instance of the class.
3. *Inheritance:* Some classes are subordinate to others and are called subclasses. Subclasses are considered to be special cases of the class under which they are grouped in the hierarchy. The variables and methods defined in the higher-level classes will be automatically inherited by the lower-level classes.
4. *Polymorphism:* Allows us to send the same message to different objects in different levels of class hierarchy. Each object responds in a way that is inherited or redefined with respect to the object's characteristics.

With these properties, integrated and expandable software for supporting designs, including design for manufacturability, can be developed. An example is shown in Trappey and Liu (1990), who developed a system shell for design using the object-oriented programming language, SMALLTALK-80 (Goldberg 1984).

Another key software technology for design for manufacturability, such as automated rule checking, is knowledge-based systems, or expert systems. The general methodology for building these systems roughly consists of five steps: identification, conceptualization, formalization, implementation, and testing (Hayes-Roth et al. 1983). An example of this approach for fixture design for machining is shown in Ferreira et al. (1985).

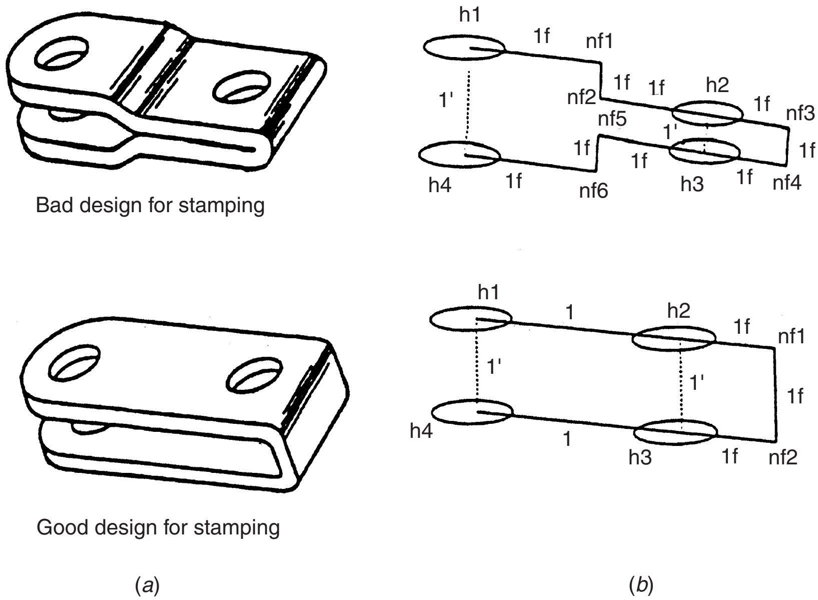


Figure 6 Parts and Their Sketching Abstractions. (*a*) Examples of stamping parts. (*b*) Parts-sketching abstraction that facilitates manufacturability evaluation in conceptual design. (Reprinted from *Robotics and Computer-Integrated Manufacturing,* Vol. 13, No. 3, A. Mukherjee and C. R. Liu, "Conceptual Design, Manufacturability Evaluation and Preliminary Process Planning Using Function–Form Relationships in Stamped Metal Parts," p. 258, Copyright 1997, with permission from Elesevier Science)

Current CAD systems have been oriented to detail design, while the application of DFM guidelines to early design stages yields the largest benefits. Research is needed to lay the foundation for the CAD system for conceptual design so that DFM and CAD can be integrated successfully. Mukherjee and Liu (1995) propose a promising method. In the proposed representation, called sketching abstraction, the discretionary geometry of the part having functional relevance is captured using functional features, while the nondiscretionary geometry is represented using a linkage mechanism. The functional features are related to the part function using data structures called function–form matrices. They attempt to bridge the gap between function and form representations and provide the designer with a tool that can be used for generating design alternatives. Figure 6 is an example of this representation, which facilitates manufacturability evaluation in conceptual design (Mukherjee and Liu 1997).

11. ORGANIZATIONAL ISSUES

Design for manufacturability is to be implemented in an industrial environment. Therefore, we are concerned with (1) increasing the individual engineer's knowledge in both the areas of design and manufacturing and (2) facilitating better and early communication between design and manufacturing groups. To increase the individual engineer's knowledge, training courses for manufacturability guidelines specific and nonspecific to the company concerned should be established. Examples, good and bad, are always helpful. Rotation of job responsibilities between design and manufacturing engineers, when feasible, is also a good way to increase an engineer's knowledge in design for manufacturability.

To facilitate better and early communication, product and process design should be managed in an integrated manner. For small companies, short product life cycle, or simple products, integrated product and process design task force may prove to be effective. For large companies, long product life cycle, or complex products, product and process engineering should be integrated within one organizational unit, or at least have a close working relationship. In large projects, computer tools may prove to be necessary. The computer tools now available are expert system software shells, CAD/CAM systems, and object-oriented programming tools, as discussed in Section 9.

In managing integrated product and process designs, there are several points worth considering:

1. Select a competent, strong project manager.
2. Quickly develop constraints for the product design and process selection at various levels by the effort of the entire team, that is, list the impossible and infeasible first.
3. Develop the product profile and specification through the team effort, remembering the purpose of a design, and list three other alternatives for every design, be it a subsystem or a component.
4. Aim high, recognizing that quality and cost need not be compromised when development time is compressed.
5. Give enough authorization to the team manager so that quick decisions can be made.

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