ABSTRACT

Title of Thesis: A MANUFACTURING PROCESS AND MATERIALS *DESIGN ADVISOR*

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A computer assisted tool, called the *DESIGN ADVISOR*, has been developed to help obtain a compatible set of candidate materials and manufacturing processes in a fast and straightforward manner. Information for seventeen manufacturing processes includes animations, written descriptions, still pictures and geometric design rules; information for forty-two materials includes written information and data. The *DESIGN ADVISOR* determines candidate manufacturing processes based on user-specified levels of one or more of seven manufacturing attributes; namely, surface condition, dimensional accuracy, complexity of shape, size, production run or production rate, and cost. The determination of candidate materials is based on the user-specified levels of one or more of eleven material attributes; namely, yield strength/density, fracture toughness/density, elastic modulus/density, high temperature strength/density, density, magnetic properties, electrical resistivity, thermal distortion, thermal insulation, solvent resistance, and cost. It also determines the suitability of candidate manufacturing processes with the candidate materials, and ranks the suitability of each candidate material within each candidate manufacturing process.

A MANUFACTURING PROCESS AND MATERIALS *DESIGN ADVISOR*

by

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DEDICATION

To my parents

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CHAPTER 1

INTRODUCTION

The introduction of a new product or new design of an existing product involves, among other things, a survey of the customer requirements, considerations of new design alternatives, feasibility evaluations of the design, selection of suitable materials and manufacturing processes, preparation of the engineering drawings, planning and scheduling of its production, marketing of the product and after sale service. The above mentioned activities cannot be performed independently of each other because it must be possible to manufacture the product using available facilities and to sell it at competitive prices while making a profit.

A product's development starts at the concept stage and ends when it is successfully marketed. In between, the product progresses through various stages. Figure 1.1 follows the various stages of a product development process.

The aim of this work is to develop a tool that will aid a product design team at the product design, materials and manufacturing processes selection stage. The product design and the materials and manufacturing processes selection is not a single step process. It is an iterative process, at the end of which the product design, materials and manufacturing processes selected are the best choices for the given product. A computer assisted tool (PC based), called the *DESIGN ADVISOR*, has been developed to help obtain a compatible set of candidate materials and manufacturing processes in a fast and straightforward manner.

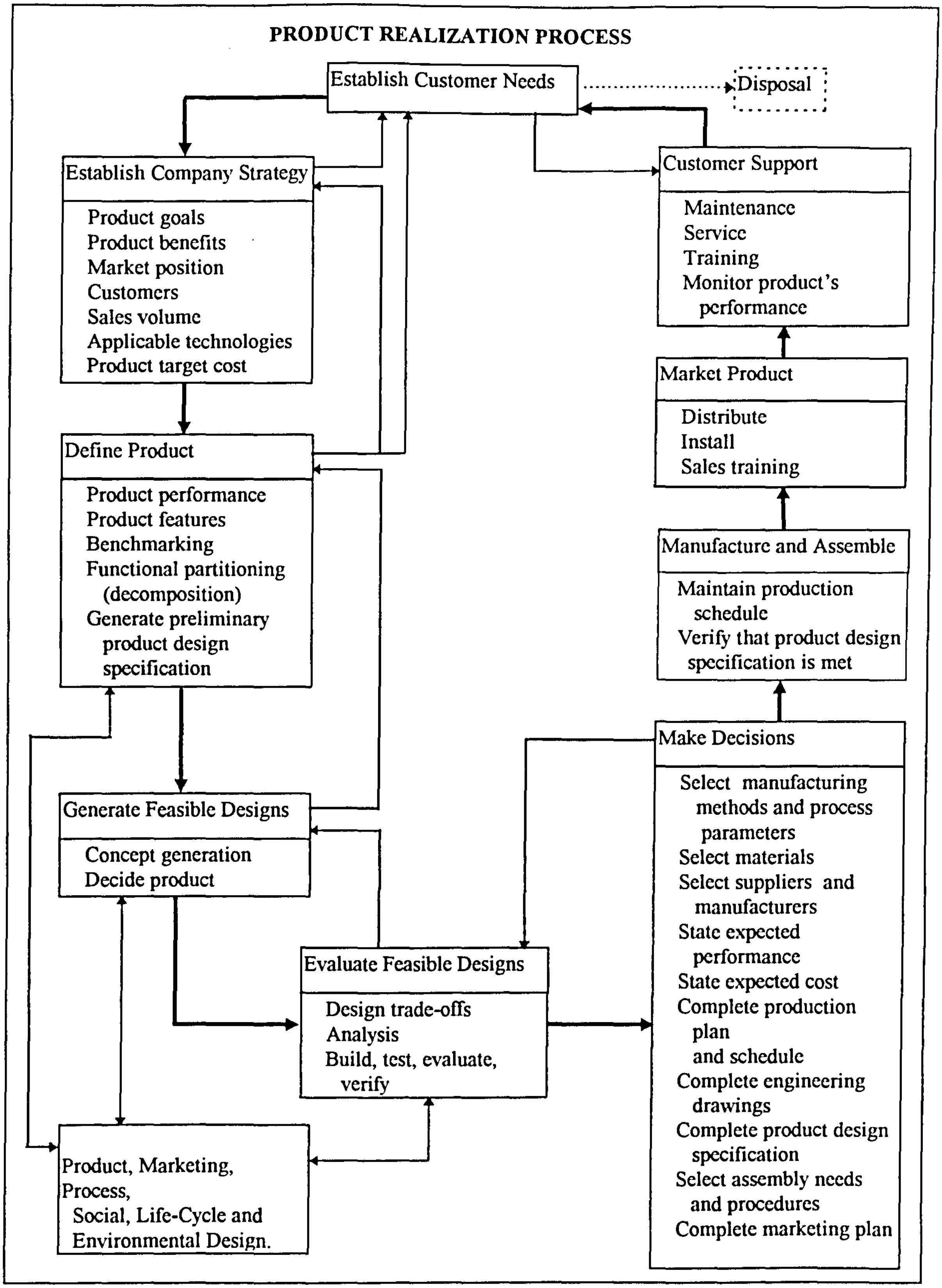


Figure 1.1 Stages in Integrated Product and Process Design and Development

1.1 Product design

While designing a product, a design team will have to answer the following questions.

- Can the number of parts and features be reduced?
- Can standard parts be used?
- What are the desired weights, sizes, shapes of the components?
- Can the product be designed for disassembly (maintainability)?
- What are the materials that can be used?

While selecting the materials for a process, the design team will have to answer the following questions.

- What are the expected failure mechanisms?
- Can the material provide the required strength to prevent failure of the product?
- Can the material provide any special physical or chemical properties that the functionality may demand?
- Can the material withstand the working environment without significant loss of properties or change in part dimensions?
- Is the material capable of being processed easily to obtain the desired shape and size that the product's functions require?

While selecting the manufacturing processes that can be used to produce the components, the design team will have to answer the following questions:

- What are the available high-quality, low-cost manufacturing processes?
- What are the capabilities of the processes?

- Do the product prototypes reflect the manufacturing process capabilities?
- What are the different manufacturing processes that need to be used to make all the components?
- Can a given manufacturing process produce the required number of parts in the given time?
- Does a given manufacturing process alter the material properties to an extent that the material is no longer suitable for the product's function?

1.2 Background

The motivation for the development of the DESIGN ADVISOR comes from the fact that there are no tools currently available that can help a high level design team obtain a workable set of suitable materials and manufacturing processes. There are a number of databases and expert systems relating to materials selection, some of which include *Cambridge Material Selector*, Cambridge University Engineering Department, Cambridge, UK; *Mat. DB,* ASM International, Metals Park, Ohio, USA; *PERITUS* Matsel Systems Ltd, Liverpool, UK; CAMPUS, Computer Aided Material Preselection by Uniform Standard, Hoechst Aktiengesellschaft, Verkauf Kunstroffe, Frankfurt, Germany. It is noted that the *DESIGN ADVISOR*'s material selection module is based on the selection attributes adopted in the *Cambridge Material Selector* and the selection levels adopted in *PERITUS*. There are, however, no tools that help a user select suitable manufacturing processes based on the manufacturing attributes of a part. There is also a lack of tools or databases that suggest the suitability of materials with manufacturing processes.

The *DESIGN ADVISOR* provides the user with a selection of suitable materials and manufacturing processes that can be used to produce a part based on several of its attributes. The *DESIGN ADVISOR* also offers design modification suggestions based on the manufacturing process selected. These suggestions are in the form of diagrammed design rules that indicate the geometric limitations of the shapes of parts for that manufacturing process. It is emphasized that the *DESIGN ADVISOR* is a high level design tool only. It is neither an optimization program, nor does it deal with sequences of processes. However, it does provide a very good means of obtaining candidate manufacturing processes and compatible materials based on a modest set of selection criteria.

CHAPTER 2

ATTRIBUTES OF MANUFACTURING PROCESSES AND MATERIALS AND THEIR RELATIONSHIP

2.1 Manufacturing process selection attributes

Manufacturing processes are selected with certain product attributes in mind. These attributes may involve the shape, size, dimensions, finish, strength, and the number of products expected to be sold. Most manufacturing processes have restrictions on the products that they can make that are based on one or more of these attributes. Certain processes cannot make products that are too small or too large, while complex features are difficult to obtain using other processes. Surface finish and dimensional tolerances affect functionality and the visual appeal of the product to the customer. The demand for a product will determine its rate of production. All of these attributes impose restrictions on the processes that can be used to manufacture the given product. Any deviation of these attributes from the normal capability of a process usually results in a significant increase in its cost. The manufacturing attributes that are most commonly specified at highest levels in the design process are:

1. Surface condition
2. Dimensional accuracy
3. Complexity (shape)
4. Production run <u>or</u> Production rate
5. Cost

6. Size

These six attributes are now discussed.

Surface condition: Surface finish is an important characteristic of a product. In many cases, products are manufactured as separate units and then assembled either by fastening (screws, bolts and rivets, etc.), or by joining (welding, brazing, soldering, adhesive bonding, etc.). Assembly by pressing and shrink fitting are also used in some applications. The surface finish of a part controls the surface appearance, affects the assembly of the part with other components and also provides some protection against corrosion and wear. There is a close relationship between surface roughness and tolerances. In general, the tolerance must be greater than the distance between the highest peak and the deepest trough of the surface roughness profile. This value is usually about 10 times the value of the average surface roughness.

Dimensional accuracy: Interchangeability of manufactured components is a standard requirement in many mass manufactured products. This has many advantages including ease of repair, ease of assembly, and standardization of manufacturing methods and products. If two or more components have to be interchangeable, then they must be manufactured to comparable dimensions. While the accuracy of certain manufacturing processes can ensure close dimensional tolerances on products, certain other processes cannot. This can be due to changes in temperature, wear of tools, deflections and vibrations in workpieces and tools, and human errors. Dimensional tolerances are the variations from the basic dimension which are permissible to ensure interchangeability of parts and define process capability. Manufacturing costs are known to increase exponentially with tighter tolerances and better surface finish. It is, therefore, important to select the surface finish and dimensional tolerances that are no better than needed.

Complexity (shape): Products vary in their shape and the complexity of their features. While most simple features can be manufactured using most of the manufacturing processes, only certain processes have the capability to produce complex features. One example is an undercut. There are many processes that will not allow the manufacture of parts with undercuts. Turning requires a part to have cylindrical symmetry, as does centrifugal casting. Powder metallurgy cannot be used to manufacture part with acute edges because of strength issues. Almost all manufacturing process cannot produce one or more complex features. Thus, the complexity of the part will determine whether or not a manufacturing process can become a candidate process to manufacture it. In the *DESIGN ADVISOR* complexity ratings are based on the number of plane that can be shaped, geometric features that can or cannot be produced by a process, etc.

Size: Products vary not only in their shapes, but also in their size. The size of the product will affect the selection of a manufacturing process. The size of a part cannot be greater than the size of the equipment used to process it.

Production run <u>or</u> production rate: Different products have different demands in the market. While common products are required in large quantities and are consumed in a short period of time (which means that the stock will have to be replenished), certain products are manufactured for special purposes; and there are cases where only a single piece is made. Various characteristics of a manufacturing process like material utilization, flexibility, equipment costs, labor costs, etc., will determine the cost of a product. Certain processes take a large set up time and cost and it is a waste of resources to manufacture a single product using these processes. All processes have a minimum number of products that must be made to economically justify the use of that process. This must be taken into account when choosing a manufacturing process.

Cost: The cost of a manufacturing process is often the single most important attribute. It is affected by all of the above attributes. Cost can be production costs, labor costs, equipment costs, etc. Since the aim of all manufacturers is to make a profit, the cost of a process will play the greatest role in its selection. The cost of a product will vary with its size, shape, production run/rate, tolerances and surface finish. Therefore, relative cost based on a sum of these effects and the ability of the process to best satisfy these requirements is used as a measure of the cost.

These seven attributes have been used as selection criteria in the *DESIGN ADVISOR* to obtain candidate manufacturing processes. It is noted that it is possible to obtain a null solution set for a given set of attributes. Care must be taken when choosing these attributes and their levels. It is best to choose the minimum number of attributes that will satisfy the most important higher level design requirements.

Table 2.1 provides important information about the degree to which various manufacturing processes satisfy the higher level design attributes. Three degrees of suitability, **H**, **M**, and **L** , where H = high, M = medium and L = low, have been provided along with their corresponding ranges and units.

2.2 Materials selection attributes

All products are made of one or more types of materials. Different products use different materials or combinations of materials, to perform one or more functions, such as carrying loads, conduct or insulate heat or electricity, withstand corrosion and wear,

Table 2.1 Manufacturing processes and their attributes [1][2][3][4].

Process	Surface roughness	Dimensional accuracy	Complexity	Production rate	Production run	Relative cost	Size (projected area)
Pressure die casting	L	H	H	M-H	H	H	L-M
Centrifugal casting	M	M	M	L	L-M	M-H	L-H
Compression molding	L	H	M	M-H	M-H	M-H	L-H
Injection molding	L	H	H	M-H	M-H	L-H	L-M
Sand Casting	H	M	M	L	L-H	L-H	L-H
Shell mold casting	L	H	H	M-H	M-H	M-H	L-M
Investment casting	L	H	H	L	L-M	M-H	L-M
Single point cutting	L	H	M	L-H	M-H	L-H	L-H
Milling	L	H	H	L-M	M-H	L-H	L-H
Grinding	L	H	M	L	M-H	M-H	L-M
EDM	L	H	H	L	L	H	L-M
Blow molding	M	M	M	M-H	M-H	L-H	L-M
Sheet metal working	L	H	H	M-H	M-H	L-H	L
Forging	M	M	M	M-H	M-H	M-H	L-H
Rolling	L	M	H	H	H	M-H	M-H
Extrusion	L	H	H	M-H	M-H	M-H	L-M
Powder metallurgy	L	H	H	M-H	H	M-H	L
H	>250	<0.005	High	> 100	>5,000	High	> 0.5
M	>63 & < 250	>0.005 & < 0.05	Medium	>10 & < 100	>100 & < 5,000	Medium	>0.02 & < 0.5
L	<63	>0.05	Low	<10	<100	Low	<0.02
Units	microinches	inch		parts/hour	parts		m^2

etc.

Material attributes may be classified under one of the following categories:

1. Mechanical and physical properties
2. Electrical, thermal and magnetic properties
3. Environmental properties
4. Cost factors

5. Production methods

Typical mechanical and physical properties are tensile and compressive strength, toughness, flexural modulus, young's modulus, fatigue strength, impact strength, hardness, destiny, creep strength, etc. At a high level in the design process, important among the above are common failure modes, weight and deformation characteristics.

Typical electrical, thermal and magnetic properties are dielectric strength, resistivity, warpage, thermal expansion, thermal conductivity, magnetic field strength, flammability, shrinkage and maximum operating temperature. Important among these at a high level in the design process are thermal conductivity, specific heat and coefficient of thermal expansion, which affect thermal distortion and thermal insulation, dielectric strength, and magnetic field strength. Although the maximum operating temperature is an important design criterion, high temperature strength is a better measure of this attribute than the melting point, i.e., temperature itself.

Environmental factors include resistance to chemical solvents, radiation, and corrosive agents. Solvent resistance has been chosen as the most commonly considered factor at a high in the level design process.

The cost of a material can be calculated as cost per unit weight, cost per unit strength, cost per unit elastic modulus, etc., depending on the application and processing. In order to keep cost factors independent from those attributes that fall in one of the other categories, relative cost has been used.

Production methods will affect the material costs. Certain materials need specific production methods to process them. The production attributes of materials imply that material selection and manufacturing process selection can not be separated. However, these factors have not been considered as attributes in the material selection part of the *DESIGN ADVISOR*. Rather, this information is used to obtain a union of candidate manufacturing processes and candidate materials. The aim of this separation is to be able to identify candidate materials based on the material attributes alone.

Having identified the major attributes in each of the categories of material properties, it is noted that it is often the case that the desired performance criteria involve a combination of two or more material attributes. For example, a high strength to weight ratio is a more meaningful attribute than high strength and low weight as two unrelated attributes. Ashby [5] has developed a simple and systematic method to obtain governing performance attributes for a given application. An attempt has been made to use some of these governing attributes. The attributes that have been chosen are:

Mechanical and physical properties:

1. Failure mode: yield strength/density

2. <u>or</u> the product of the maximum service temperature, T_{max} and the strength at T_{max} (a measure of high temperature strength)

3. <u>or</u> fracture strength/density

4. Elastic modulus/density

5. Density

Electrical, magnetic and thermal properties:

6. Dielectric strength

7. Magnetic field strength

8. Thermal insulation

9. Thermal distortion

Environmental factors:

10. Solvent resistance

Cost factors:

11. Relative material cost

These nine attributes are now discussed.

Yield strength/density: Strength is an extensible property, that is, the strength of a component can be increased by increasing its size. The increase in size of a component will result in increased volume and weight and increased material costs. Ideal materials are those that can provide high strength with reasonably sized components. These materials are said to have high "structural efficiency." Structural efficiency depends not only on the strength of the component, but also on the loading and the geometry of the component. The structural efficiency of a component is usually of the form σ^k/ρ, where σ is the maximum stress depending on the expected mode of failure, k is a number that depends on the loading and the geometry of the component, and ρ is the density of the material [5]. The structural efficiency term will favor materials that have high strength and low weight, i.e., a low weight design is usually desirable. In the *DESIGN ADVISOR* σ_{yld} , the tensile yield strength, is chosen as the strength that will determine failure. The value of k is set to 1, this being the most common value of k.

Fracture toughness/density: Brittle materials tend to crack before they fail in yield. Fracture toughness over density (K_{IC}/ρ), is a useful parameter that can indicate the efficiency of a material in resisting failure by fracture for a given section thickness.

Elastic modulus/density: Elastic modulus is a measure of the stiffness of a material. Stiffness is the ability of a material to maintain its shape when acted upon by a load. The stiffness of the material of a component will determine the deflections it undergoes, the amount of energy it can absorb, and whether or not it can fail by buckling. While increasing the strength of a material allows one to decrease the section thickness, the metallurgical strengthening methods do not change the young's modulus of the material. Thin sections in compression can fail by buckling, since they lack the geometric stiffness as determined by the moment of inertia of the cross section. Depending upon the loading conditions and the geometry of the component, the design parameter that affects failure, either by buckling or by the magnitude of deflections, is of the form E^k/ρ, where E is the youngs modulus, k is a number that varies with the geometry of the section and the nature of the loading and ρ is the density of the material. For simplicity, k is set to 1.

High temperature strength/density: Most materials perform satisfactorily at room temperatures, but their strength decreases rapidly as the temperature increases. While the melting point of a material is an indication of its high temperature strength characteristics, it is not a reliable parameter. Most materials have a working temperature range in which there is a very small decrease in the yield strength. At higher temperatures, the yield strength begins to drop rapidly. The product of the maximum working temperature (the temperature at which the yield strength drops to 80% of its value at room temperature) and the average yield strength in this working temperature range is a good measure of the high temperature strength capabilities. An example of the usefulness of such a parameter would be where a higher working temperature is more desirable than higher strength. A material with a slightly lower yield strength, but a larger working temperature range will be more useful than a material with a higher yield strength, but a narrow working temperature range. The parameter $(\sigma_{yld}T_{max})/\rho$, where σ_{yld} is the average yield strength in the working temperature range, T_{max} is the maximum working temperature and ρ is the density of the material, is a useful parameter to determine the high temperature strength of a material. The product of σ_{yld} and T_{max} has been divided by the density ρ to incorporate the weight of the material.

Density: The density of a material ρ has been used as an independent selection parameter. Often the aim of a manufacturer is to minimize the cost. Hence the density of the material will indicate weight for a given geometry and size. The density of a material will also affect transportation and material handling issues. The density will decide which of the feasible solutions will satisfy the above mentioned issues to the degree desired.

Magnetic property: Applications involving electromagnetic equipment require materials that can function as permanent or semi-permanent magnets. Certain other applications will find magnetic materials disadvantageous, since this property can interfere with the normal functioning of certain types of electronic equipment. The magnetic property is chosen as a useful parameter that will decide whether or not a material is a candidate for a given application.

Electrical resistivity: Many components need to conduct electricity to work properly, others need to be non-conductors. As more and more machines work on electrical power, there is a need to select suitable conductors and insulators to ensure proper functioning of this type of equipment. Electrical resistivity is a measure of the insulating capability of a material and is used to select electrical conductors and insulators.

Thermal distortion: Many components need to work in varying temperature environments. However, a change in the temperature of the working environment can cause a change in the dimensions of a component. This is especially critical in components that need to maintain tolerances or need to work over a wide temperature range. Thermal distortion depends not only on the coefficient of thermal expansion, but also on the thermal conductivity of a material, since it is caused by high thermal gradients across the material.

Consider the case of one-dimensional heat flow through a rod insulated except at its ends. In the steady state, Fouriers law is:

$$q = -\lambda \, dT/dx$$

where q is the heat input per unit area, λ is the thermal conductivity and dT/dx is the temperature gradient.

The strain is related to temperature by

$$\varepsilon = \alpha(T_o - T)$$

where α is the thermal conductivity and T_o is the ambient temperature. Thus,

$$d\varepsilon/dx = \alpha dT/dx = [\alpha/\lambda] \, q$$

Therefore, for a given geometry and heat flow, the distortion *dε/dx* is minimized by selecting materials with large values of λ/α [5].

Thermal insulation: The performance index that determines the suitability of such a material to hold its temperature for long periods of time is $a^{1/2}/\lambda$ [5](where a is the thermal diffusivity and λ is the thermal conductivity of the material). Insulating materials have low heat capacities as well. Materials with high values of this performance index serve as good insulators.

Solvent resistance: Many components are exposed to various chemicals like acids, bases, solvents, etc., during their use. Materials react in different ways to different chemicals and this interaction can affect the functioning and life of the component. Solvent resistance is selected as a characteristic having wide application. For plastics, resistance to UV and fire retardation are important considerations. However, they have been omitted because they are properties that are not common with the candidate metals.

Cost: While there are a number of new materials with excellent properties that are finding increased use, it is noted that these materials are not always needed. A costlier material does not justify its use unless there is no less expensive material that can meet the requirements. When selecting a suitable material, the final choice may depend on its cost. Relative cost is chosen as a selection parameter, where the relative cost is the ratio of the cost of a material in dollars/pound to the cost of polyethylene in dollars/pound.

These attributes have been used as selection criteria in the *DESIGN ADVISOR* to obtain candidate materials. It is noted that it is always possible to obtain a null solution

Table 2.2 Relationship of various materials to several material selection parameters [5][6][7][8][9]

Material	Yield strength/density	Creep strength/density	Fracture toughness/density	Youngs modulus/density	Density
Low carbon steel	M	M-H	H	H	H
Medium carbon steel	M-H	M-H	M	H	H
High carbon steel	M-H	M-H		H	H
Low alloy steel	M-H	M-H	L-H	H	H
Tool steel	M-H	M-H	L-H	H	H
Stainless steel	L-H	M-H	M-H	H	H
Gray iron	L	L	L	M-H	H
Malleable iron	L-M	M-H	L-M	H	H
Ductile iron	L-M	L-H	L-M	H	H
Alloy cast iron				H	H
Zinc alloys	L-M	L	L-M	M-H	H
Aluminum alloys	L-H	L-H	M-H	H	M
Magnesium alloys	L-H	L-H	M	H	L
Titanium alloys	M-H	M-H	L-H	H	M
Copper alloys	L-H		L-H	M-H	H
Nickel alloys	L-H	L-H	M-H	H	H
Tin alloys	L-M			L-H	H
Cobalt alloys	M			H	H
Molybdenum alloys	M			H	H
Tungsten alloys	L-M		L	H	H
Low expansion alloys	L-H			H	H
Permanent magnet alloys					M-H
Electric resistance alloys				H	H
ABS	L-M	L	L	L	L
Acetals	M	L		L	L
Nylons	L-M	L-M	L	L	L
Fluorocarbons	L	L		L	L
Polycarbonates	M	L	L	L	L
Polyimides	L-M	L-M		L	L
Polystyrene	L-M	L	L	L	L
PVC	L-M	L	L	L	L
Polyurethane	L-M	L	L	L-M	L
Polyethylene	L-M	L	L	L	L
Polypropylene	L-M	L	L	L	L
Acrylics	M			L	L
Alkyds	L-M	L-M		L-H	L
Epoxies	L-H	L-H	H	L-M	L
Phenolics	L-M	L-M		L-H	L
Silicones	L	L		L-M	L-M
Polyester	L-H	L-H	L	M-H	L
Rubbers					L
Cellulosics	L-M	L		L	L
Units	KPa/kg/m^3	MPa °C/kg/m^3	Kpa m$^{1/2}$ /kg/m^3	MPa/kg/m^3	kg/m^3
H	>100	>30	>10	>15	>5000
M	>30 <100	>10 <30	>5 <10	>5 <15	>2500 <5000
L	<30	<10	<5	>5	<2500

Table 2.2(Continued) Relationship of various materials to several material selection parameters

Material	Magnetic property	Resistivity	Thermal distortion	Thermal insulation	Solvent resistance	Relative cost
Low carbon steel	M-H	L	L-M	L	M-H	L
Medium carbon steel	M-H	L	M	L	M-H	L
High carbon steel	M-H	L	M	L	M-H	L
Low alloy steel	M-H	L-M	L-H	L-M	M-H	H
Tool steel	M-H		M-H		M-H	H
Stainless steel	M-H	L	M-H	L-M	M-H	H
Gray iron	M-H		M		M-H	L
Malleable iron	M-H		M		M-H	L
Ductile iron	M-H	M	M	L	M-H	L
Alloy cast iron	M-H	M	L-H		M-H	L
Zinc alloys	L	L	L-M	L	M-H	M
Aluminum alloys	L	L	L-M	L	M-H	M
Magnesium alloys	L	L	L-H	L-M	M-H	H
Titanium alloys	L	M	L		M-H	H
Copper alloys	L	L	L-H	L-M	M-H	H
Nickel alloys	H	L-M	L-H	L-M	M-H	H
Tin alloys	L	L	M	L-M	M-H	
Cobalt alloys	H	M	L		M-H	H
Molybdenum alloys	L	L	L	L	M-H	H
Tungsten alloys	L	L	L	L	M-H	H
Low expansion alloys	L	L-M	L-H	M	M-H	
Permanent magnet alloys	H	L-M			M-H	
Electric resistance alloys	L	L-M	H	M	M-H	
ABS	L	M	H	L-H	L	M
Acetals	L	H	H	L-H	M	M-H
Nylons	L	H	H	L-H	M	H
Fluorocarbons	L	H	H	L-H	M-H	H
Polycarbonates	L	H	H	L-H	L	H
Polyimides	L	H	L-H		M	H
Polystyrene	L	H	H	L-H	L	L-M
PVC	L	H	H	L-H	L	M
Polyurethane	L	H	H		L	
Polyethylene	L	H	H	L-H	M	L
Polypropylene	L	H	H	L-H	M	L-M
Acrylics	L	H	H		L	M-H
Alkyds	L	H	M			M
Epoxies	L	H	M-H	L-H	M-H	M
Phenolics	L	H	L-H		M	M
Silicones	L	H	H		L	
Polyester	L	H	M-H		M-H	H
Rubbers	L					
Cellulosics	L	H	H	L-H	L	
Units		micro ohm cm	W/micro m	KJ $s^{1/2}/m^2$ K		
H		>10000	<2	<5		>2.0
M		>25 < 10000	>2 <5	>5 <10		>1.0 <2.0
L		<25	>5	>10		<1.0

set for a set of selected attributes. Care must be taken when choosing these attributes and their respective levels. The aim is to choose the minimum number of attributes that will satisfy the requirements.

Table 2.2 provides important information about the degree to which various materials satisfy the higher level design attributes. Three degrees of suitability, **H**, **M**, and **L** , where H = high, M = medium, and L = low, have been provided, along with their corresponding range and units.

2.3 Union of candidate manufacturing processes and candidate materials

Any product development strategy stresses the need to combine material selection with the choice of the manufacturing process. To perform this "union" of the candidate materials and candidate manufacturing processes to obtain suitable material-manufacturing process combinations, a knowledge based approach has been used. The existing literature has abundant information about typically used materials in a chosen manufacturing process and vice versa. This information has been used to construct Table 2.3, which provides important information about the degree of suitability of a manufacturing process and a material. Four degrees of suitability have been used. They are:

'E' which indicates excellent compatibility between the material and the manufacturing process.

'G' which indicated good compatibility between the material and the manufacturing process.

'S' which means that the material and the manufacturing process are seldom used in combination with each other.

'-' which means that the material is not processed or is not recommended to be processed using this manufacturing process.

The importance of constructing a table of this nature is to eliminate incompatible materials and manufacturing processes. Such incompatibilities may necessitate a redesign of the product, including modifications to the functional requirements of the product.

The formulation of a table based on the literature has one disadvantage. New and previously unused material-manufacturing process combinations that may actually be suitable for a product will not be considered. The chances of such unknown combinations are, however, very small. Moreover, the identification of attributes and how they affect the degree of suitability is very unclear. For these reasons, the table has been constructed using only well-established knowledge.

Table 2.3 is then used to combine candidate manufacturing processes and candidate materials, and to give each combination a figure of merit. This figure of merit includes the degree of suitability of the manufacturing process for the given set of manufacturing attributes, the degree of suitability of the materials for the given set of material attributes, and the degree of suitability of the material with the manufacturing process.

Table 2.3 The suitability of materials and manufacturing processes [1][2][3][4]

Material	Pressure die casting	Centrifugal casting	Compression molding	Injection molding	Sand casting	Shell mold casting	Investment casting	Single point cutting	Milling	Grinding	EDM	Blow molding	Sheet metal working	Forging	Rolling	Extrusion	Powder metallurgy
Low carbon steel	-	E	-	-	E	E	E	G	G	E	E	-	G	G	G	G	E
Medium carbon steel	-	E	-	-	E	E	E	G	G	E	E	-	G	G	G	G	E
High carbon steel	-	E	-	-	E	E	E	G	G	E	E	-	G	G	G	G	E
Low alloy steel	-	E	-	-	E	E	E	-	G	E	E	-	G	G	G	G	E
Tool steel	-	-	-	-	G	E	E	-	-	-	E	-	-	-	-	-	E
Stainless steel	-	G	-	-	E	E	E	-	-	-	E	-	G	G	G	G	E
Gray iron	-	E	-	-	E	E	E	G	G	E	E	-	G	S	S	S	E
Malleable iron	-	E	-	-	E	E	E	G	G	E	E	-	G	S	S	S	E
Ductile iron	-	E	-	-	E	E	E	G	G	E	E	-	G	S	S	S	E
Alloy cast iron	-	E	-	-	E	E	E	G	G	E	E	-	G	S	S	S	E
Zinc alloys	E	-	-	-	G	G	S	G	-	S	E	-	E	S	S	G	E
Aluminum alloys	E	E	-	-	E	G	E	E	E	G	E	-	E	E	E	E	E
Magnesium alloys	E	-	-	-	E	G	E	G	-	S	E	-	G	S	G	E	E
Titanium alloys	-	-	-	-	-	G	S	-	-	S	E	-	-	G	S	S	E
Copper alloys	G	E	-	-	E	G	G	E	E	G	E	-	E	E	E	E	E
Nickel alloys	-	E	-	-	E	G	G	-	-	S	E	-	G	S	G	G	E
Tin alloys	E	-	-	-	G	G	S	-	-	S	E	-	S	-	S	S	E
Cobalt alloys	-	-	-	-	-	G	G	-	-	S	E	-	-	-	-	-	E
Molybdenum alloys	-	-	-	-	-	G	G	-	-	S	E	-	-	-	-	-	E
Tungsten alloys	-	-	-	-	-	G	G	-	-	S	E	-	-	S	-	-	E
Low exp. alloys	-	E	-	-	E	G	G	-	-	S	E	-	G	S	G	G	E
Perm. magnet alloys	-	E	-	-	E	G	G	-	-	S	E	-	G	S	G	G	E
Electric resist. alloys	-	E	-	-	E	G	G	-	-	S	E	-	G	S	G	G	E
ABS	-	-	-	-	-	-	-	G	G	G	-	G	-	-	-	E	-
Acetals	-	-	-	-	-	-	-	G	G	G	-	G	-	-	-	G	-
Nylons	-	-	-	E	-	-	-	G	G	G	-	G	-	-	-	G	-
Fluorocarbons	-	-	-	-	-	-	-	G	G	G	-	G	-	-	-	S	-
Polycarbonates	-	-	-	-	-	-	-	G	G	G	-	G	-	-	-	G	-
Polyimides	-	-	-	-	-	-	-	G	G	G	-	G	-	-	-	S	-
Polystyrene	-	-	-	E	-	-	-	G	G	G	-	G	-	-	-	E	-
PVC	-	-	-	-	-	-	-	G	G	G	-	G	-	-	-	E	-
Polyurethane	-	-	E	-	-	-	-	G	G	G	-	G	-	-	-	G	-
Polyethylene	-	-	-	E	-	-	-	G	G	G	-	E	-	-	-	E	-
Polypropylene	-	-	-	-	-	-	-	G	G	G	-	E	-	-	-	E	-
Acrylics	-	-	-	-	-	-	-	G	G	G	-	-	-	-	-	S	-
Alkyds	-	-	E	-	-	-	-	G	G	G	-	-	-	-	-	S	-
Epoxies	-	-	E	E	-	-	-	G	G	G	-	-	-	-	-	S	-
Phenolics	-	-	E	-	-	-	-	G	G	G	-	-	-	-	-	G	-
Silicones	-	-	E	-	-	-	-	-	-	-	-	-	-	-	-	S	-
Polyester	-	-	E	-	-	-	-	G	G	G	-	-	-	-	-	S	-
Rubbers	-	-	E	E	-	-	-	-	-	-	-	-	-	-	-	S	-
Cellulosics	-	-	-	-	-	-	-	G	G	G	-	-	-	-	-	S	-

CHAPTER 3

SALIENT FEATURES OF THE *DESIGN ADVISOR*

3.1 The manufacturing process selection module

The salient features of the manufacturing processes' selection module are as follows. The user -

- Can select certain manufacturing attributes of the part and their respective levels.
- Can review the selections and modify, delete or add attributes.
- Can obtain a list of the candidate manufacturing processes that satisfy the selected manufacturing attributes.
- Can obtain a figure of merit based on the degree of suitability of the process to the manufacturing attributes selected.
- Can access all the information available in the information module of the *DESIGN ADVISOR* from the manufacturing selection module.
- Can either save the results to a file or print it.
- Can go back and modify one or more of the attributes and their levels and obtain a new solution set.

The advantage of the last feature is that the user can try different attribute sets and study how the solution space changes. This is especially useful when the initial solution space is very small. Eliminating an attribute or changing the level of an attribute may expand the solution space and provide the user with a larger number of options. This is highly desired at a higher level design process where the greater the number of options, the better the chances are of obtaining a good design.

The manufacturing process selection module utilizes the information provide in Table 2.1 and the user requirements. Processes that have the capability of satisfying the user requirements are retained and assigned a figure of merit, while those that are unsuitable are eliminated as candidates.

3.2 The material selection module

The salient features of the materials selection module are as follows. The user -

- Can select the material attributes of the part and their respective levels.
- Can review the selections and modify, delete or add attributes.
- Can obtain a list of the candidate materials that satisfy the material attributes.
- Can obtain a figure of merit based on the degree of suitability of the material to the material attributes selected.
- Can access all the information available in the information module of the *DESIGN ADVISOR* from the materials selection module.
- Can either save the results to a file or print it.
- Can go back and modify one or more of the attributes and their levels and

obtain a new solution set.

The advantage of the last feature is that the user can try different attribute sets and study how the solution space changes. This is especially useful when the initial solution space is very small. Eliminating an attribute or changing the level of an attribute may expand the solution space and provide the user with a larger number of options. This is highly desired at a higher level design where the greater the number of options, the better the chances are of coming up with a good design.

The materials selection module utilizes the information provide in Table 2.2 and the user requirements. Materials that have the capability of satisfying the user requirements are retained and assigned a figure of merit, while those that are unsuitable are eliminated as candidates.

3.3 The union of materials and manufacturing processes module:

The salient features of the union module are as follows. The user -

- Can select the material and manufacturing attributes of the product and their respective levels.
- Can review the selections and modify, delete or add attributes.
- Can obtain a list of the candidate materials and candidate manufacturing processes that satisfy the selected material and manufacturing attributes respectively.
- Can determine, from the list of the candidate materials and manufacturing

processes, the materials that are suitable for use with each manufacturing process. Each material within each manufacturing process is given a figure of merit based on the degree of suitability of the material to satisfy both the material attributes and the manufacturing attributes selected. In other words, it determines and ranks the compatibility of the material for that manufacturing process.

- Can access the information available in the information module of the *DESIGN ADVISOR* while comparing the various candidate material and manufacturing process combinations.
- Can either save the results to a file or print it.
- Can go back and modify one or more of the attributes for either the materials or the manufacturing processes or both, and their respective levels and obtain a new solution set.

The advantage of the last feature is that the user can try different attribute sets and study how the solution space changes. This is especially useful when the initial solution space is very small. Eliminating an attribute or changing the level of the attribute may expand the solution space and provide the user with a larger number of options. This is highly desired at a higher level in the design process, where the greater the number of options, the better the chances are of coming up with a good design.

The union module utilizes the information provide in Table 2.3 and the user requirements. Materials-manufacturing process pairs that are compatible are retained and assigned a figure of merit, while those that are incompatible are eliminated as candidates.

3.4 The information module

3.4.1 Manufacturing processes: The manufacturing process information module is a show-and-tell tool that can be used to explain a process, its attributes and its capabilities. The 17 manufacturing processes that have been selected are classified under three basic groups and their subgroups. Figure 4.6 gives the classification adopted.

Information about each of these manufacturing processes has been divided into:

1. Text, which contains:

   - *Process description*: A short description of the process and the individual steps involved in manufacturing a part from start to finish using this process.
   - *Material utilization*: The material utilization capability of the product, high fair or low, depending on the amount of material waste in the process.
   - *Flexibility*: The ease with which the process can be adapted to produce a new part.
   - *Cycle time*: The average production time for a part using this process.
   - *Operating costs*: The cost issues relating to the tooling, material costs, and labor costs.
   - *Quality*: Surface finish and dimensional accuracy that can be obtained using this process .

- *Shapes*: The complexity of parts that can be made, and their sizes.
- *Products*: Typical products that have been manufactured by this process.
- *Materials*: Typical materials that are used in this process.
- *Advantages*: Specific advantages of the process.
- *Disadvantages*: Specific disadvantages of the process.

Appendix A includes the text about the manufacturing processes available in the *DESIGN ADVISOR*.

2. Animations:

A brief animation of each of the manufacturing processes has been created. The animation depicts the main sequence of operations that are performed in the process that modify the raw material into the final shape. Depending on the process, sectional views have been used in the animations to show what goes on inside the equipment during the process. The animations are three dimensional and have a realistic appearance. Standard video features like play, stop, pause, rewind, forward, and frame-by-frame advance have been provided to help the user view the animation and the sequence of operations clearly.

3. Still pictures:

Still pictures have been provided for each of the manufacturing processes. Each still displays the typical equipment that is used in the process with all important functional parts clearly shown and labeled. Appendix B includes the stills in the *DESIGN*

ADVISOR.

4. Design rules:

Most processes have a set of design rules, which if followed, should minimize the cost of manufacturing a product and produce a better part. The design rules are a set of pictures with text explaining the do's and don'ts of the manufacturing practices. Appendix C includes the design rules in the *DESIGN ADVISOR.*

3.4.2 Materials

The 42 important materials that have been selected have been classified into two main groups, metals and non-metals. These groups are then divided into a number of subgroups. Figure 4.10 shows the classification scheme that has been adopted.

Information about each of these materials has been divided into:

1. Text, which contains:

- Information about the material and its composition.
- Special properties of the material.
- Specific applications of each material based on its properties.

Appendix D includes the text available in the *DESIGN ADVISOR.*

2. Data sheets:

Several important properties of the material have been provided for quick reference and/or for comparison purposes. The numerical values can be switched between American units and SI units.

CHAPTER 4

THE *DESIGN ADVISOR* MODULES PROGRAM LOGIC

4.1 General outlay of program logic

The programs begins, as shown in Figure 4.1, with a welcome screen [Figure E.1, Appendix E], after which it prompts the user to choose one of the following three choices [Figure E.2, Appendix E]:

1. Conduct a search or obtain information on manufacturing processes.
2. Conduct a search or obtain information on materials.
3. Conduct a search of manufacturing processes and their suitable materials.

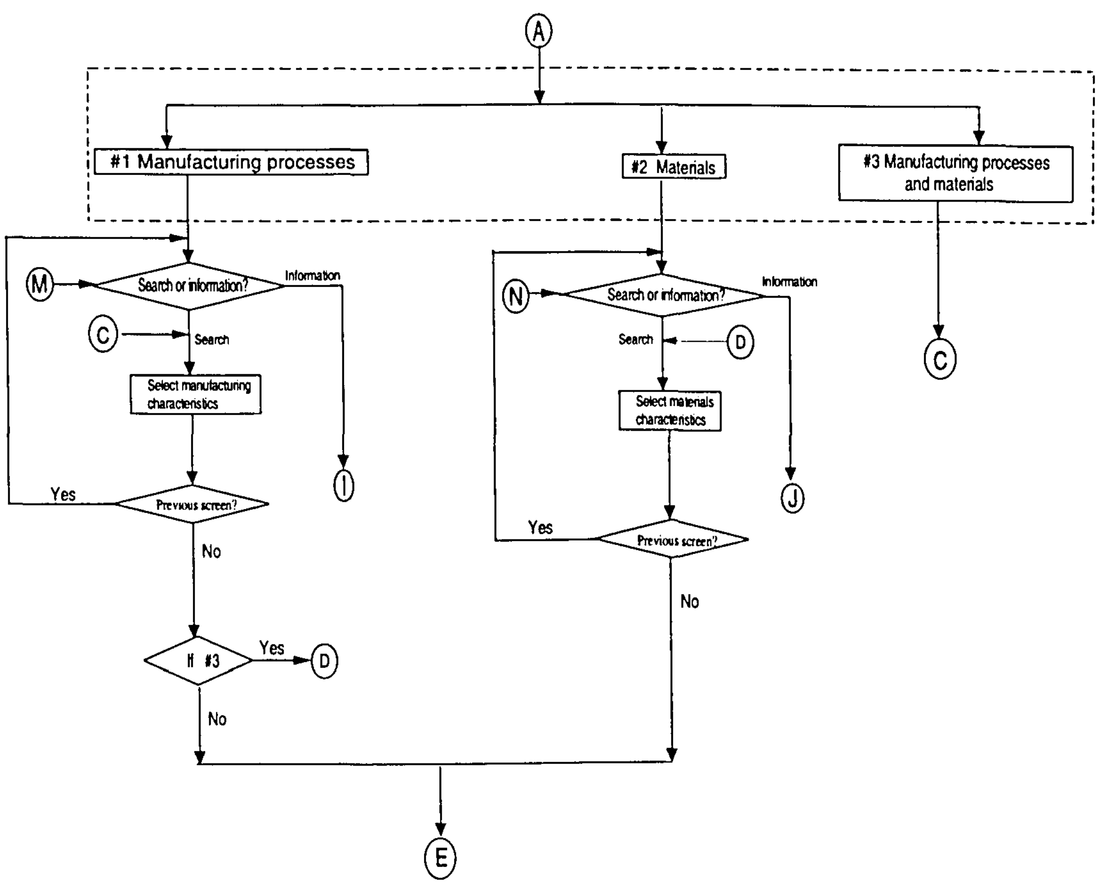


Figure 4.1 Flowchart of the *DESIGN ADVISOR*. [also see Figures 4.2, 4.7, and 4.9]

Selection of either options #1 or #2 brings up a new screen [Figure E.3, Appendix E or Figure E.4, Appendix E], which queries the user to determine if the user wants to obtain information about either manufacturing processes or materials or to conduct a search of either the candidate manufacturing processes or materials.

Search: If the user wants to conduct a search of the candidate manufacturing processes or materials, the user is provided with the manufacturing attributes [Figure E.5, Appendix E] or material attributes [Figure E.6, Appendix E].

The manufacturing attributes are surface finish, dimensional accuracy, complexity, size, shape and production run or production rate. The material attributes are yield strength/density or fracture toughness/density or creep strength/density, elastic modulus/density, density, magnetic property, resistivity, thermal insulation, thermal distortion, solvent resistance and cost. Each attribute has three levels, high medium and low. Numerical values with suitable units when applicable, are displayed to indicate what each level means for the selected attribute. After selecting an attribute, the user is prompted either to select one of the three levels of the attribute or to cancel the selection. The selected attributes and their levels are displayed on the same screen in a different color and font size to help the user identify the selections.

If the user wants to conduct a search of the candidate manufacturing processes and their materials, the manufacturing attributes are chosen first and then the material attributes are selected. It is noted that this order is not crucial to the program logic.

Figure 4.2 shows the five choices appearing on the next screen, wherein the user is given an opportunity either to review the manufacturing attributes, the material

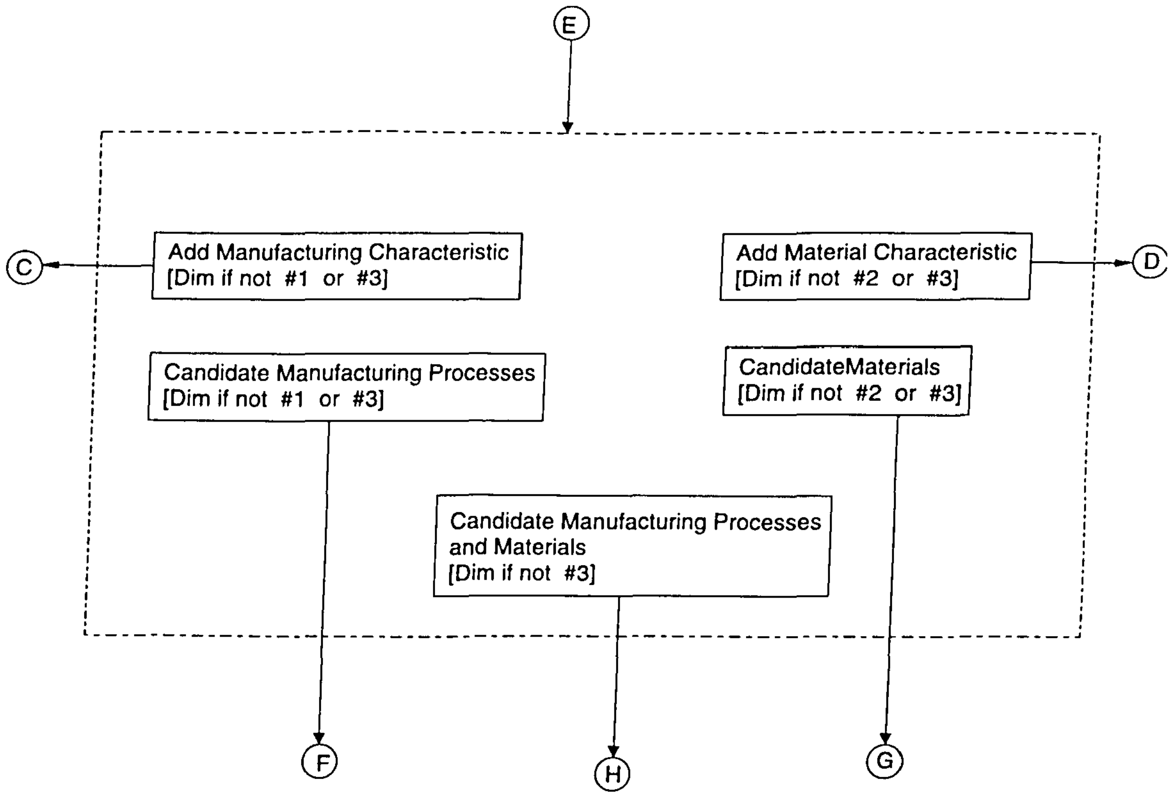


Figure 4.2 Flowchart of the *DESIGN ADVISOR* [continued] [also see Figures 4.1, 4.3, 4.4, and 4.5]

attributes or both, depending on the type of search selected. Each box in Figure 4.2 [Figure E.7, Appendix E] represents an item that the user can activate with the mouse.

At this stage the user can either modify the levels of the selected attributes, delete the attributes from the selection criterion list or add new attributes to the list. At the end of the modification process the user can view either the candidate manufacturing processes, the candidate materials or the candidate manufacturing processes and their materials, depending on the nature of the search.

4.2 Determination of candidate manufacturing processes

The candidate manufacturing processes are determined using a routine that is activated when the user selects the option to determine the candidate manufacturing processes.

This routine reads in the relevant manufacturing attributes data of all the manufacturing processes. It then compares the ability of each of the manufacturing process to provide the desired level of each of the selected attributes. A manufacturing process is eliminated from the list of candidates if it fails to satisfy any one of the attributes at their desired levels. This sorting routine is explained in detail in Section 4.5. Figure 4.3 indicates the options available to the user once the candidate manufacturing processes

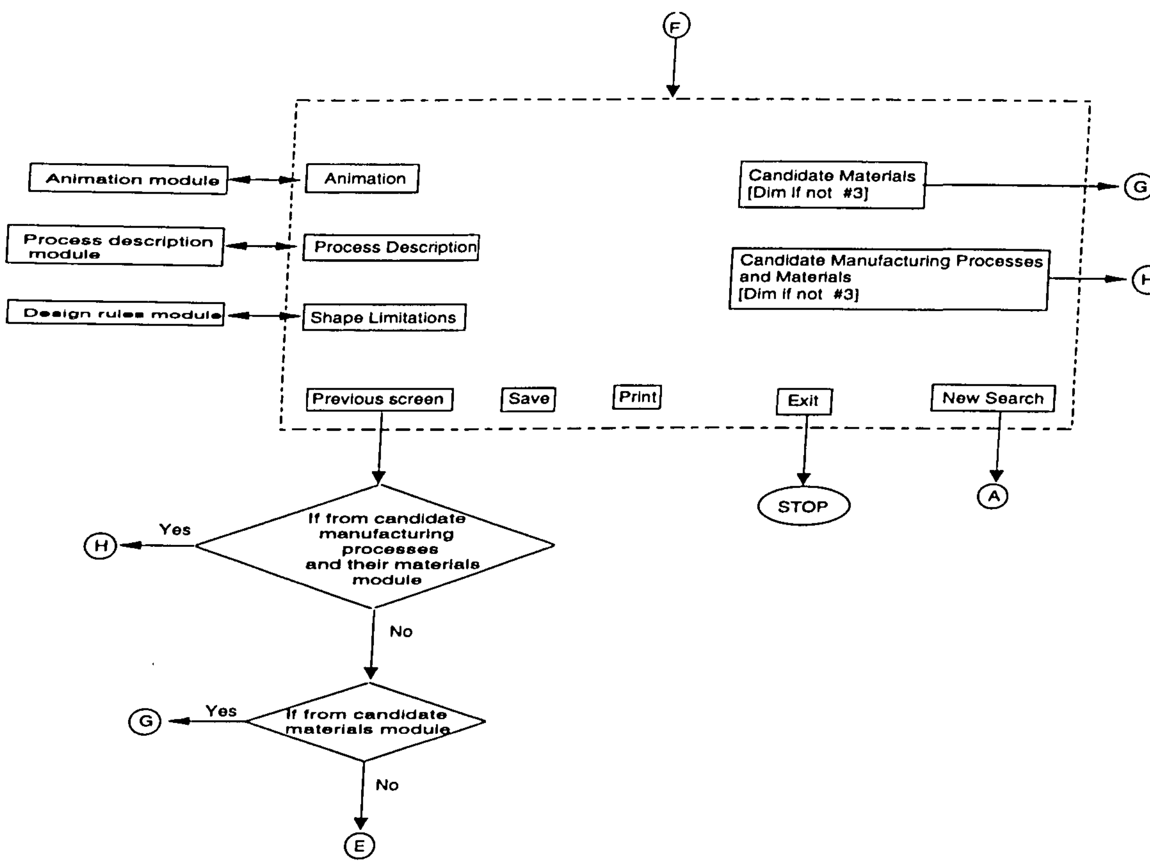


Figure 4.3 Flowchart of the *DESIGN ADVISOR* [continued] [also see Figures 4.1, 4.2, 4.4, and 4.5]

are determined. Each box in Figure 4.3 [Figure E.8, Appendix E] represents an item that the user can activate with the mouse. The user can view an animation of the process, read or print a description of the process and its capabilities, and study the design rules associated with manufacturing components using the selected process. The user can also save or print the list of candidate manufacturing processes along with the attributes and the levels that were used to obtain this solution set.

4.3 Determination of candidate materials

The candidate materials are determined using a routine that is activated when the user selects the option to view the candidate materials. This routine reads in the relevant material attributes data of all the materials. It then compares the ability of each of the materials to provide the desired level of each of the selected attributes. A material is eliminated from the list of candidates if it fails to satisfy any one of the attributes at their desired levels. This sorting routine is explained in detail in Section 4.5.

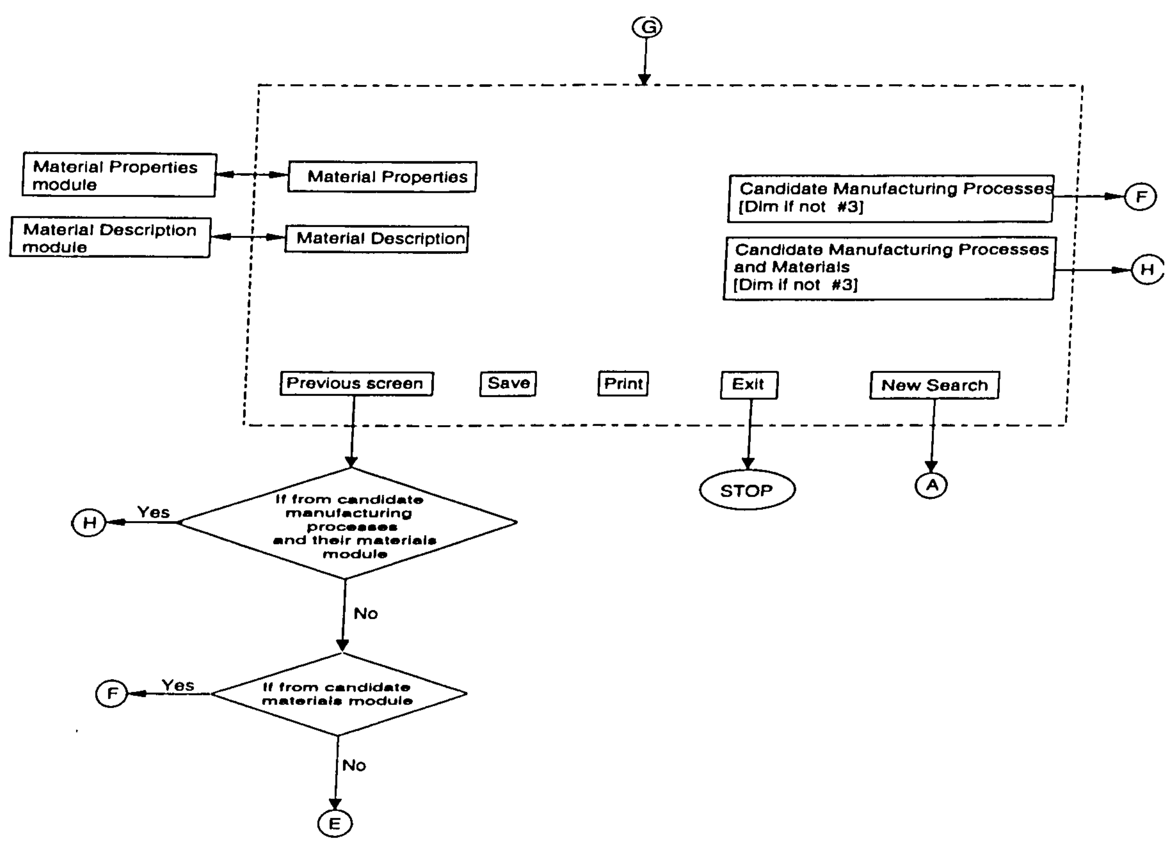


Figure 4.4 Flowchart of the *DESIGN ADVISOR* [continued] [also see Figures 4.1, 4.2, 4.3, and 4.5]

Figure 4.4 indicates the options available to the user once the candidate materials are calculated. Each box in Figure 4.4 [Figure E.9, Appendix E] represents an item that the user can activate with the mouse. The user can read or print a description of the material and its applications, and obtain a data sheet containing some important properties of the materials.

The user can also save or print the list of candidate materials along with the attributes and the levels that were used to obtain this solution set.

4.4 Determination of candidate manufacturing processes and their materials

A search of the manufacturing processes and their materials is conducted when the user selects the option to view the candidate manufacturing processes and their materials. This search involves three stages. In the first stage, all candidate manufacturing processes are determined based on the desired manufacturing attributes. In the second stage, all candidate materials are determined based on the desired material attributes. The third and final stage involves the union of the candidate manufacturing processes and the candidate materials. In this stage a sorting routine selects a candidate manufacturing process. It then evaluates each of the candidate materials for compatibility with the manufacturing process. This evaluation is done using the data given in Table 2.3. This sorting routine is explained in detail in Section 4.5. Manufacturing process-material combinations that are not compatible are eliminated from the solution list.

Each solution is given a qualitative figure of merit. This figure of merit is a measure of the suitability of the manufacturing process to the manufacturing attributes, the material to the material attributes, and the manufacturing process to the material.

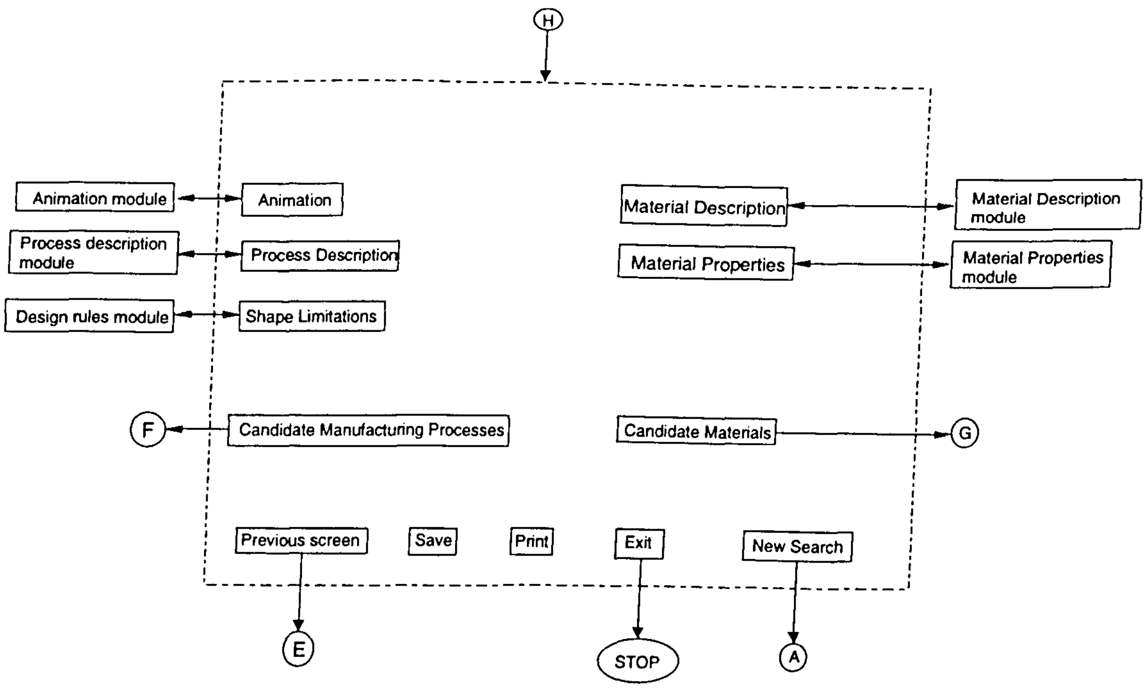


Figure 4.5 Flowchart of the *DESIGN ADVISOR* [continued] [also see Figures 4.1, 4.2, 4.3, and 4.4]

Figure 4.5 displays the options available to the user once the candidate manufacturing processes and their materials have been determined. Each box in Figure 4.5 [Figure E.10, Appendix E] represents an item that the user can activate with the mouse. The user can either view an animation of the process, read or print a description of a process and its capabilities or study the design rules associated with manufacturing components using the selected process. The user can read or print a description of a material and its applications, and obtain a data sheet containing some important properties of the materials. The user can also save or print the list of candidate manufacturing processes and their materials, along with the attributes and the levels that were used to obtain this solution set.

Information: If the user wants to obtain information about either the manufacturing processes or materials, the user is provided with the classification of manufacturing processes or the classification of materials, respectively.

4.5 Information on manufacturing processes

The manufacturing processes have been classified under three main divisions: casting, forging and machining. Figure 4.6 [Figure E.11, Appendix E] is a representation of the classification of the manufacturing processes. Each box in the two right hand "columns" of Figure 4.6 represents an item that the user can activate with the mouse.

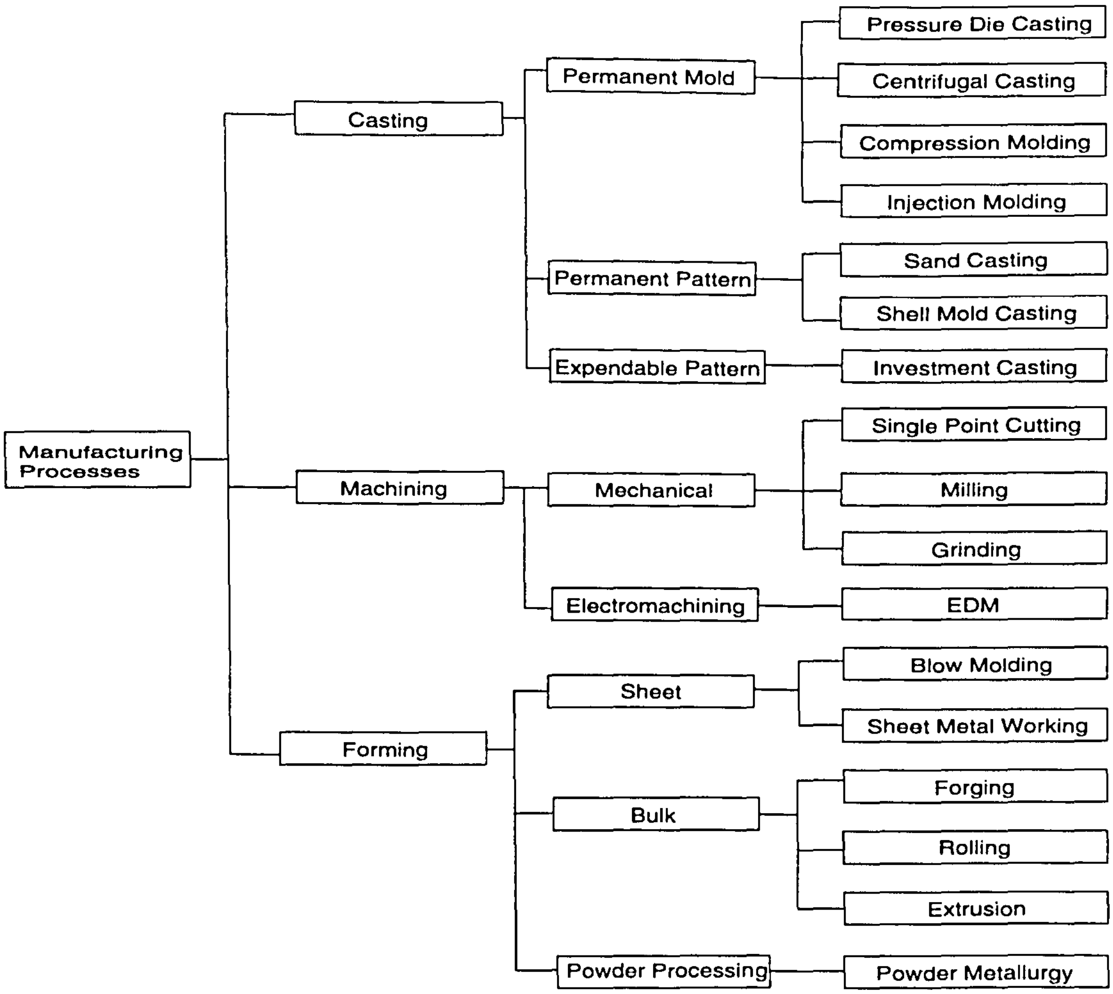


Figure 4.6 Classification of manufacturing processes

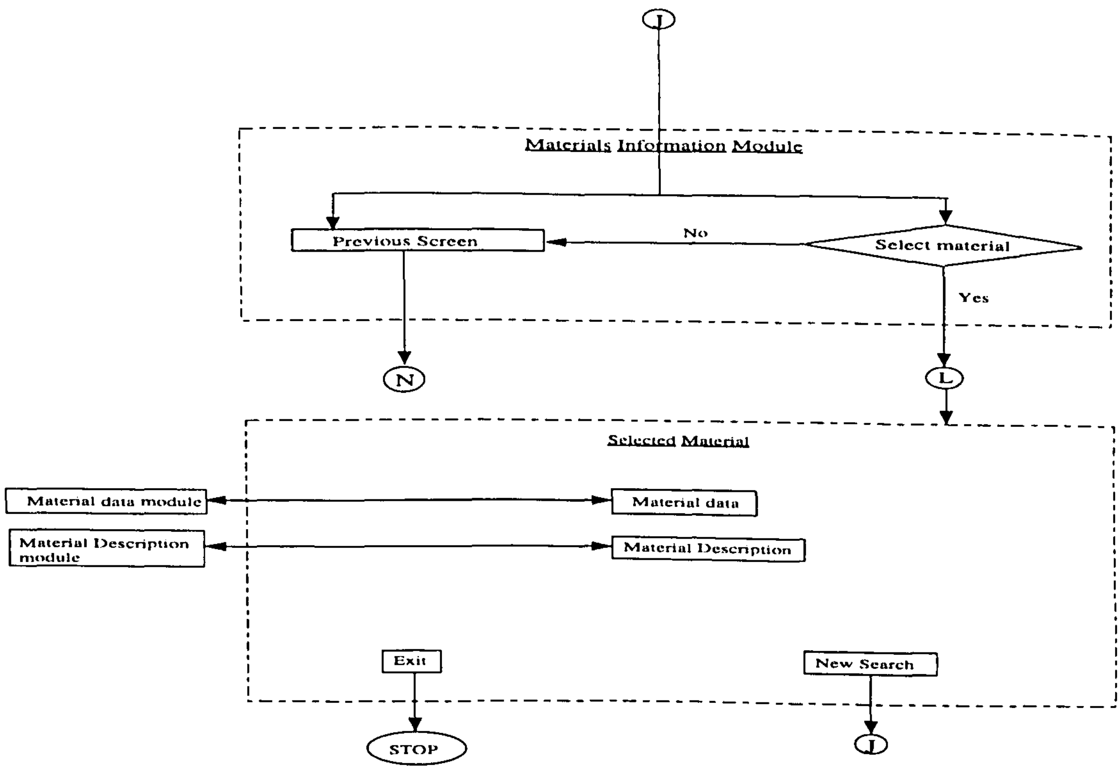


Figure 4.7 Flowchart of the *DESIGN ADVISOR* [continued] [also see Figure 4.1]

On selecting a manufacturing process, the user can view an animation or a still picture of the process, read or print a description of a process and its capabilities, and study the design rules associated with manufacturing components using the selected process [Figure E.13, E.14, E.15 and E.16, Appendix E]. Figure 4.7 [Figure E.12, Appendix E] is a representation of the flowchart of this part of the *DESIGN ADVISOR*. Each box in Figure 4.7 represents an item that the user can activate with the mouse.

4.6 Information on materials

The materials have been classified into two broad areas, metals and plastics. The metals are further classified as ferrous alloys, non-ferrous alloys or special purpose alloys, and the plastics are further classified as thermoplastics or thermosets. The details of these further classifications are show in Figure 4.8b and 4.8c, respectively. Each box in the right hand "column" of Figures 4.8a, 4.8b, and 4.8c [Figure E.17 and Figure E.18, Appendix E] represents an item that the user can activate with the mouse.

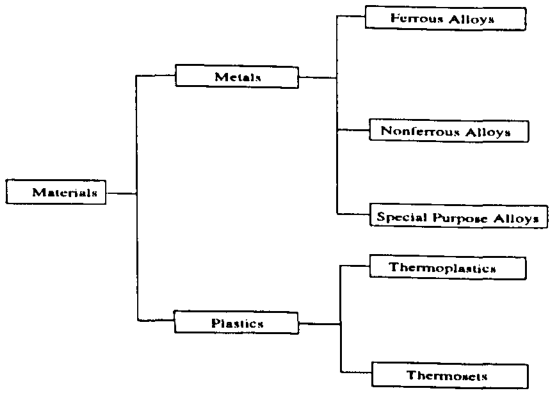


Figure 4.8a Classification of materials

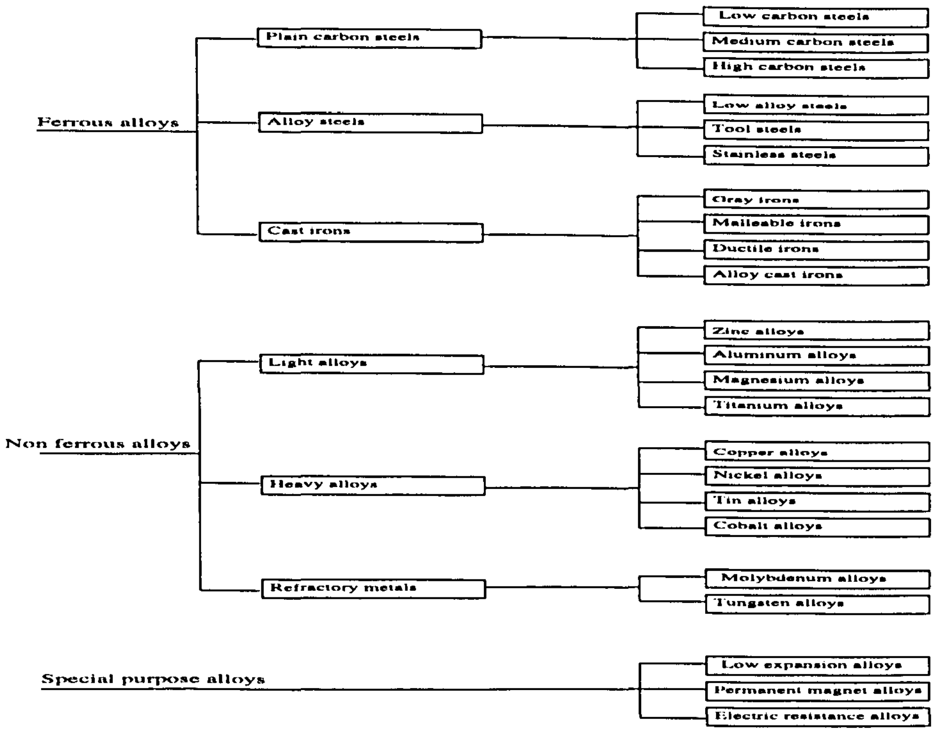


Figure 4.8b Classification of materials [continued]

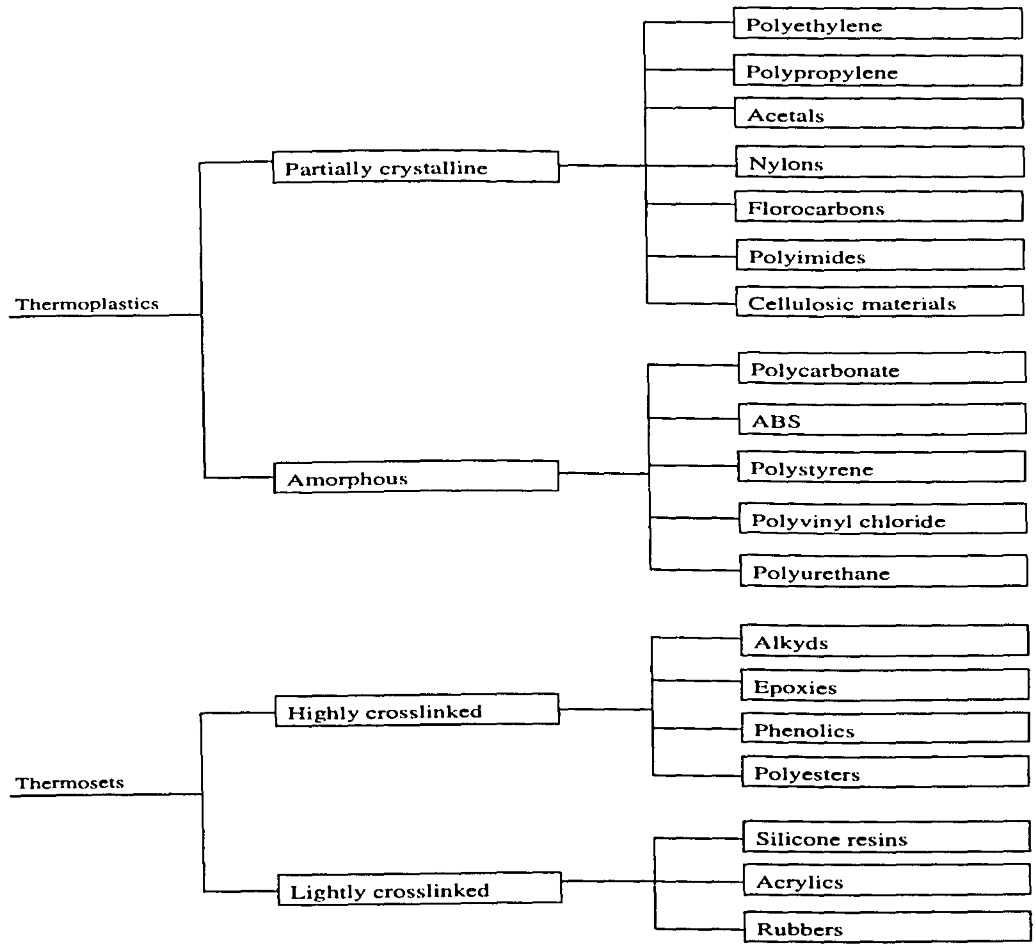


Figure 4.8c Classification of materials [continued]

On selecting a material, the user can either read or print a description of the material and its applications [Figure E.20, Appendix E] and obtain a data sheet [Figure E.21, Appendix E] containing some important properties of the material. Figure 4.9 is a representation of the flowchart of this part of the *DESIGN ADVISOR*. Each box in Figure 4.9 [Figure E.19, Appendix E] represents an item that the user can activate with the mouse.

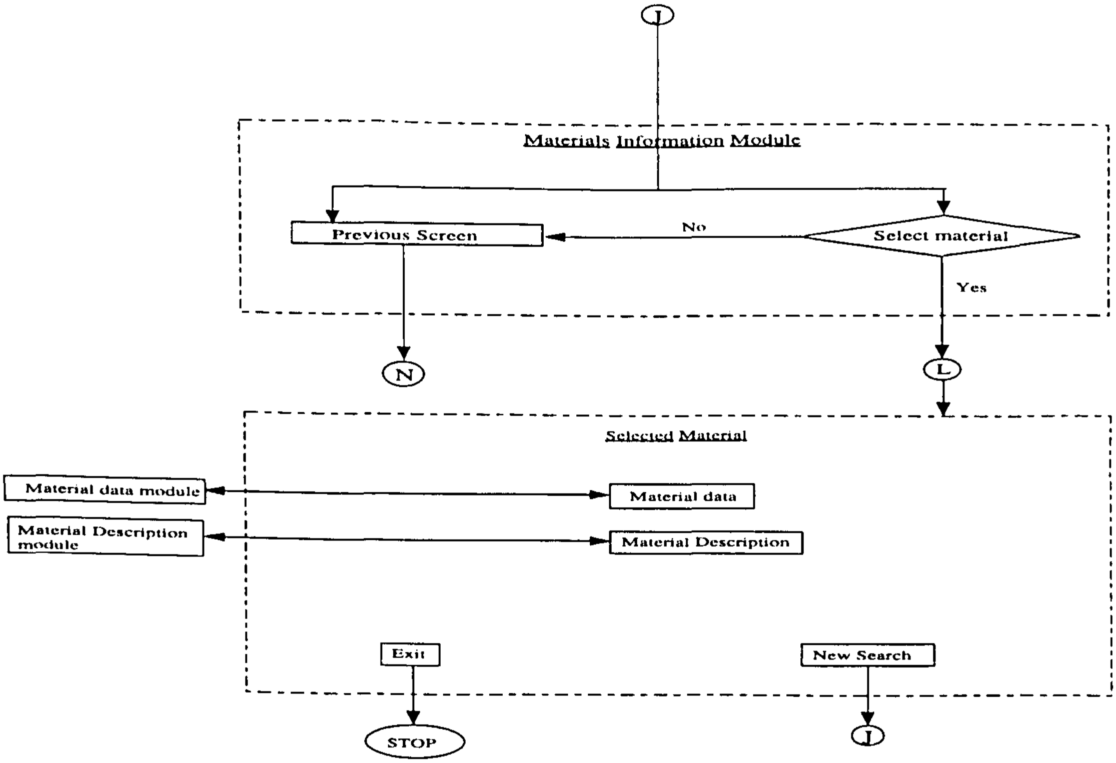


Figure 4.9 Flowchart of the *DESIGN ADVISOR* [continued] [also see Figure 4.1]

4.7 The sorting routine

The sorting routine has three distinct parts: (1) the manufacturing process sorting; (2) the materials sorting; and (3) the manufacturing processes and materials union sorting.

Manufacturing process sorting: This sorting routine uses the data in Table 2.1. Table 2.1 contains seven manufacturing attributes, referred to as *Pattribute(I), I*=1,...7, and seventeen manufacturing processes, referred to as *Process(J), J*=1,...17. Each attribute corresponding to each manufacturing process can have selected either one, or two adjacent or all three levels: High, Medium and Low. Each of these manufacturing processes and their corresponding attributes has these levels stored as *ManTable(J,I)*. At the start of the sort, all manufacturing processes have a flag called the *ProcessFlag* set to

TRUE. After the user has selected one or more of these seven attributes, they are stored in *Pattribute.Level(I)*. The sorting routine first selects *Pattribute*(1). If *Pattribute*(1) has not been selected by the user, then it examines *Pattribute*(2). If the user has selected *Pattribute*(1), then the routine selects *Process*(1). If the process is capable of providing the desired attribute level then *ProcessFlag*(1) remains set to TRUE. In other words, all the *Pattribute.Level*(1)'s that have been selected are a subset of *ManTable.Level(J,I)*, which are all the levels that the process is actually capable of satisfying, as explained in Fig 4.11. If the process is not capable of providing the desired attribute level(s), this flag

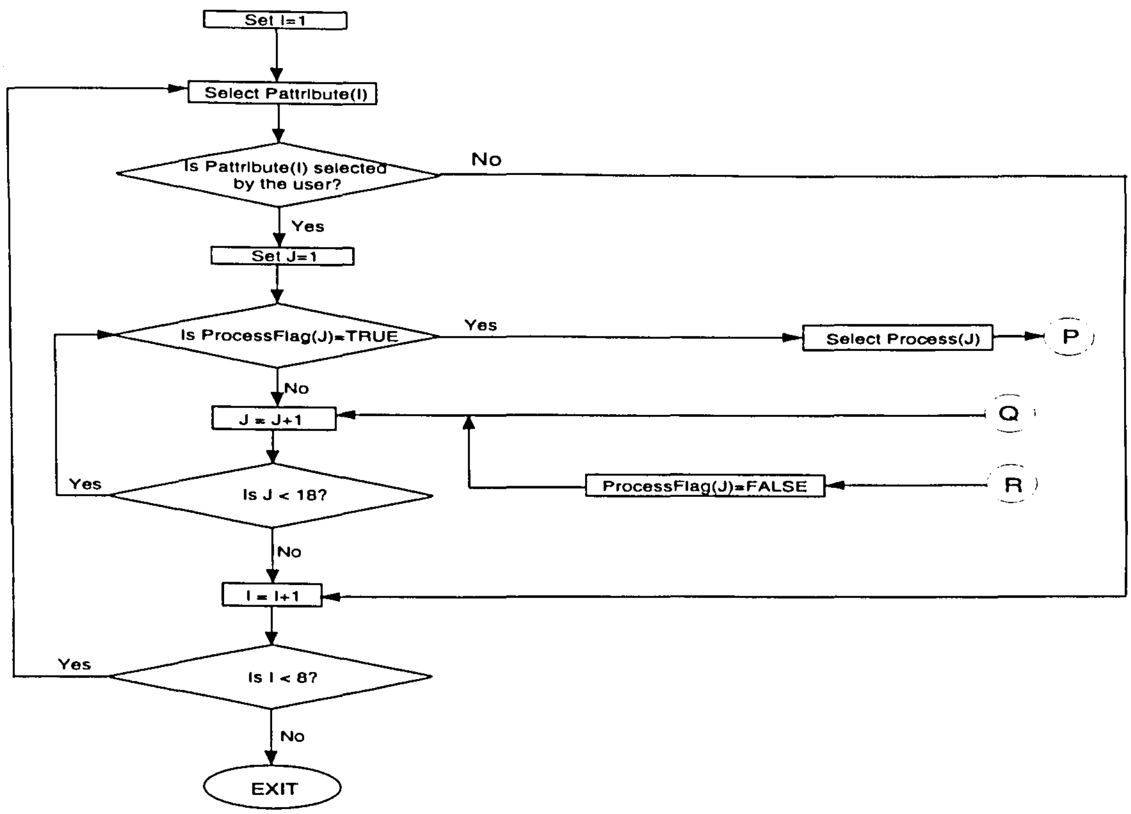


Figure 4.10 Manufacturing processes sorting [also see Figure 4.11]

is set to FALSE and the manufacturing process is eliminated from the search. The routine then examines the next manufacturing process and the procedure is repeated until all the manufacturing processes have been tested. Then the next attribute is examined and those manufacturing processes whose flag remains TRUE are examined to determine whether or not they can satisfy the level(s) of the attribute selected. The final candidate manufacturing processes are those that still have the *ProcessFlag* set to TRUE. Figure 4.10 contains a flow chart of the manufacturing process sorting routine.

Elimination of unsatisfactory materials or manufacturing processes:

Fig. 4.11 explains how unsatisfactory materials or manufacturing processes are eliminated from the sorting procedure. It is noted that the variable *Attribute.Level(I)* is

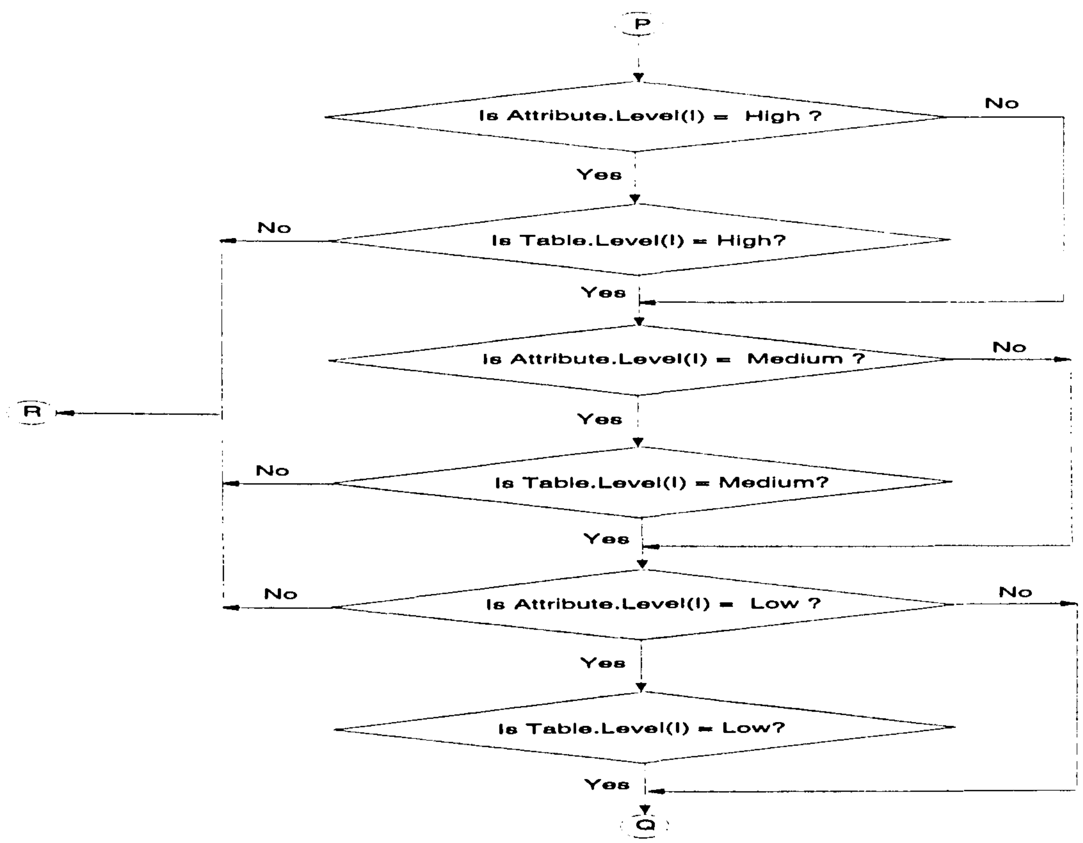


Figure 4.11 Elimination of manufacturing processes or materials [also see Figures 4.10 and 4.12]

either *Pattribute.Level(I)* for a manufacturing process elimination or Mattribute.Level(I) for a material elimination; similarly, the variable *Table.Level(J,I)* is either

*ManTable.Level(J,I)*for a manufacturing process elimination or *MatTable.Level(J,I)* for a materialelimination. This routine is called at the point ***P*** in Figures 4.10 and 4.12. If one of the user selected attribute levels, *Attribute.Level(I)* = High, then if *Table.Level(J,I)* ≠ High, then the manufacturing process or the material is no longer a candidate and this module returns to point ***R*** in Figures 4.10 and 4.12 and the process or material is eliminated from the search. for a manufacturing process elimination or *MatTable.Level(J,I)* for a material elimination. If *Table.Level(J,I)* = High, then the material or manufacturing process is still a possible candidate and the routine evaluates the next *Attribute.Level(I)*. If for a manufacturing process or a material, *Attribute.Level(I)* ≠ High, then the module moves to the next *Attribute.Level(I)* and repeats this test. At the end of the comparision, a candidate manufacturing processes or materials is returned to point ***Q*** in Figures 4.10 and 4.12, respectively, while the unsatisfactory manufacturing processes or unsatisfactory materials are returned to point ***R*** in Fig. 4.10 and Fig. 4.12 respectively.

Materials sorting: This sorting routine uses the data in Table 2.2. Table 2.2 contains eleven material attributes, referred to as *Mattribute(I), I*=1,...11, and forty-two materials, referred to as *Material(J), J*=1,...42. Each attribute corresponding to each material can have selected either one, or two adjacent or all three levels: High, Medium and Low. Each of these materials and their corresponding attributes has the level(s) stored as *MatTable(J,I)*. At the start of the sort, all materials have a flag called the *MaterialFlag* set to TRUE. After the user has selected one or more of these eleven attributes, they are stored in *Mattribute.Level(I)*. The sorting routine first selects

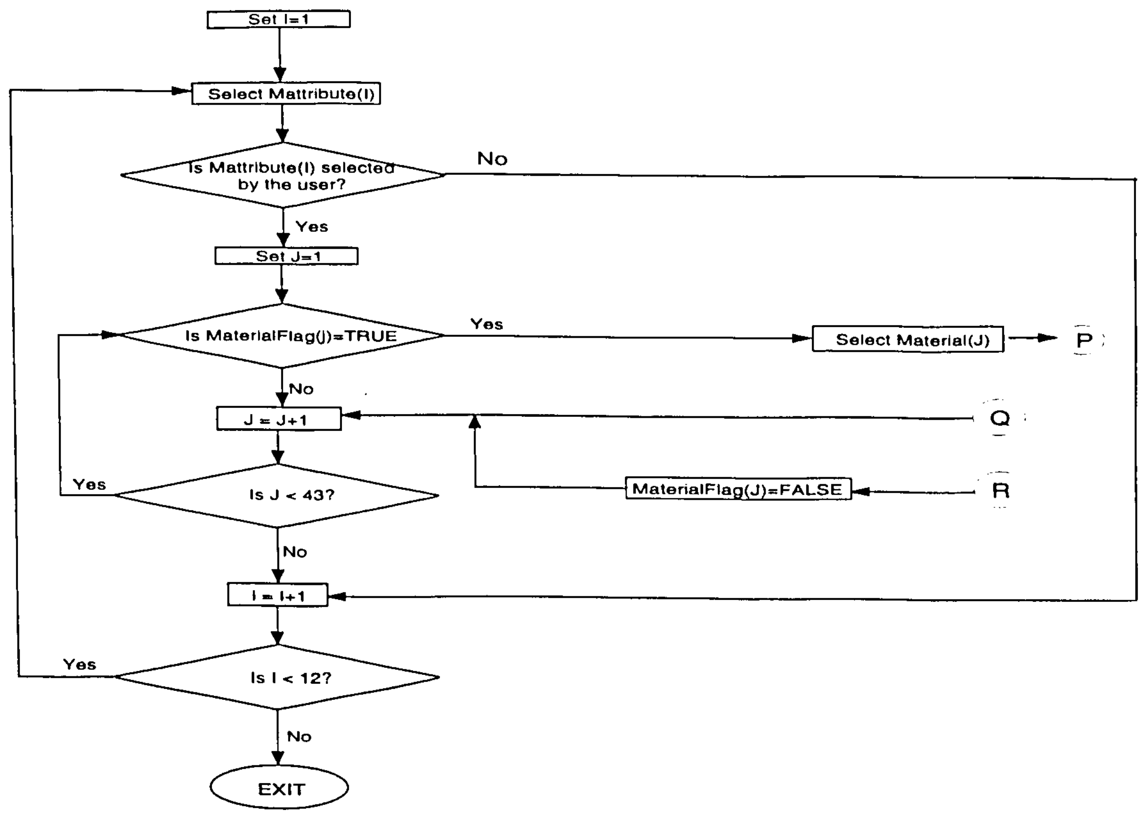


Figure 4.12 Materials sorting [also see Figure 4.11]

Mattribute(1). If *Mattribute*(1) has not been selected by the user, then it examines *Mattribute*(2). If the user has selected *Mattribute*(1), then the routine selects *Material*(1). If the material is capable of providing the desired attribute level then *MaterialFlag*(1) remains set to TRUE. In other words, all the *Mattribute.Level*(1)'s that have been selected are a subset of *MatTable.Level(J,I)*, which are all the levels that the material is actually capable of satisfying, as explained in Fig 4.11. If the material is not capable of providing the desired attribute level(s), this flag is set to FALSE and the material is eliminated from the search. The routine then examines the next material and the procedure is repeated until all the materials have been tested. Then the next attribute is examined and the remaining materials are examined to determine whether or not they can satisfy the level(s) of the attribute selected. The final candidate materials are those that still have the *MaterialFlag* set to TRUE. Figure 4.12 contains a flow chart of the materials sorting routine.

Manufacturing processes and materials union sorting: Before this sorting routine is executed, the manufacturing processes sorting routine and the materials sorting routine are executed to obtain the candidate manufacturing processes and the candidate materials. Then this sorting routine uses the information in Table 2.3 to determine the suitability of the candidate materials with the candidate manufacturing processes. The suitability is in form of a set of values referred to as *UnionTable(J,I)* which provide a numerical value indicating the suitability of *Material(J)*, *J*=1...42, with *Process(I)*, *I*=1,...17.

Initially, a flag, *UnionFlag(J,I)* is set to FALSE. The routine first selects manufacturing process, *Process*(1). *If Process*(1) is not a candidate manufacturing process, (i.e, *ProcessFlag*(1) = TRUE after the manufacturing process sorting is completed), the routine examines *Process*(2). If *Process*(1) is a candidate manufacturing process the routine then examines *Material*(1). If *Material*(1) is not a candidate material (i.e., *MaterialFlag*(1) = FALSE after the materials sorting in completed), then it examines *Material*(2). If *Material*(1) is a candidate material, then if the suitability parameter *UnionTable(J,I)* is greater than zero, then the manufacturing process-material combination is added to the list of solutions by setting *UnionFlag(J,I)* to TRUE; if not, the combination is discarded. The routine then looks for the next *Material(J)*. This iscontinued until all manufacturing process-material pairs have been tested for suitability.

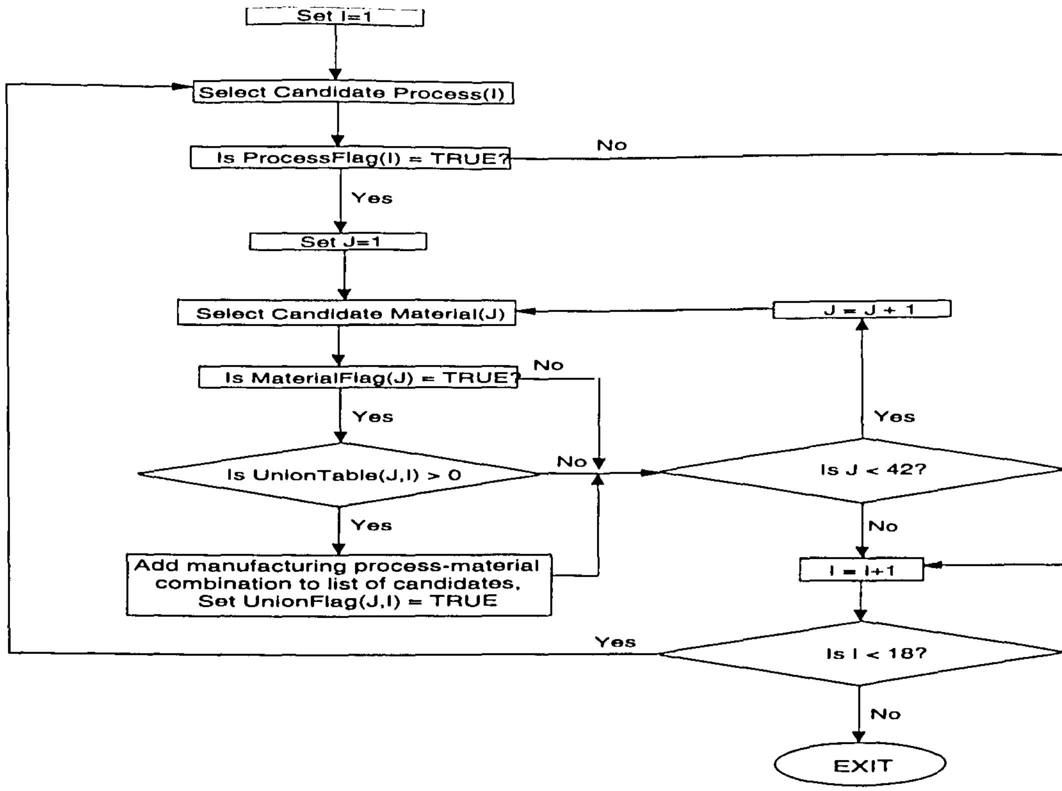


Figure 4.13 Manufacturing processes and materials union.

The final candidate manufacturing process and material combinations are those that have the *UnionFlag* set to TRUE. Figure 4.13 contains a flow chart of the manufacturing process and materials union sorting routine.

CHAPTER 5

CASE STUDIES USING THE *DESIGN ADVISOR*

These examples are given to illustrate the power of the *DESIGN ADVISOR*.

Example 1 Material selection for a golfball printhead [5]

Golfball print heads have two main requirements. They should have high strength to withstand failure during use, and they should have a low inertia so that they can accelerate and decelerate very fast.

Requirements:

High strength

Low inertia

Solutions in Ashby[5]:

Nylons, epoxy, cast magnesium alloys, cast aluminum alloys

Selection attributes in the DESIGN ADVISOR:

Yield strength/density: High

Density: Low/Medium

Solutions of the DESIGN ADVISOR:

Magnesium alloys, aluminum alloys, titanium alloys, epoxies, polyester (nylon).

Example 2 Material selection for a precision instrument [5]

Precision instruments need to avoid distortion. While materials can maintain given dimensions at a specified temperatures, when the ambient temperature fluctuates, thermal gradients are more crucial in determining the distortion of material. These materials also need to avoid vibrations at their natural frequency to provide accurate data measurement.

Requirements:

Low distortion

High natural frequencies

Solutions in Ashby[5]:

Diamonds, silicon, beryllium, aluminum, silver, copper, gold, tungsten, molybdenum, invar, silicon nitride.

Selection attributes in the DESIGN ADVISOR:

Thermal distortion: High

Elasticity/density: Low/Medium

Solutions of the DESIGN ADVISOR:

Magnesium alloys, aluminum alloys, titanium alloys, copper alloys, nickel alloys, molybdenum alloys, tungsten alloys, low expansion alloys, phenolics, low carbon steels, low alloy steels, alloy cast irons.

Example 3 Manufacturing process selection for turbine blades [G.Dieter, suggestion]

Requirements:

Surface finish: Good

Tolerances: Good

Complexity: High

Production run: Low

Size: Medium/Large

Currently used methods:

Precision forging followed by form milling.

Selection attributes in the DESIGN ADVISOR:

Surface condition: Low/Medium

Dimensional accuracy: Medium/High

Complexity: High

Production run: Low

Size: Medium/High

Solutions of the DESIGN ADVISOR:

EDM, investment casting, milling. It is noted that due to the sequence of operations, and the fact that precision forging is used as a special intermediate process, it does not show up in the candidate solutions.

It is noted from the above examples that the *DESIGN ADVISOR* is able to almost duplicate the solution sets (based on the materials and manufacturing processes available in its database). In addition to this, it also offers new candidate solutions that are not currently in use, but which could possibly satisfy the same requirements.

CHAPTER 6

CONCLUSIONS AND FUTURE EXTENSIONS TO THE *DESIGN ADVISOR*

6.1 Advantages of the *DESIGN ADVISOR*

The *DESIGN ADVISOR* provides a PC based tool that can assist a design team to rapidly obtain suitable manufacturing processes, materials or a combination of manufacturing processes and their materials based on a very straightforward set of selection criteria. In addition to manufacturing process and materials selection, it provides a large amount of information about individual manufacturing processes and materials. This information can help a design team make appropriate modifications to both the selection of manufacturing processes and materials as well as the design of the part itself. The *DESIGN ADVISOR* also moves away from the conventional material selection techniques based on a single property, and incorporates the use of more useful parameters like specific strength, rather than just strength, and thermal distortion, rather than just the coefficient of thermal expansion.

The advantages of the *DESIGN ADVISOR* are:

- It is a unique higher level design tool that can be used to obtain suitable materials and/or manufacturing processes for a given set of part attributes.
- It can be used as an effective educational tool to emphasize the interrelationship among materials, manufacturing processes and the geometric attributes of the design.
- It is a very flexible tool that allows the user to move forwards and backwards

to effect changes to the selections when desired.

- It provides figures of merit to quantify the suitability of a material and/or manufacturing process to the selected part attributes.

- It links the candidate solution selection modules to the information modules allowing the user to obtain specific and detailed information about a candidate solution.

- It obtains the candidate solutions in real time, thus making the *DESIGN ADVISOR* an ideal tool for the integrated product and process design and development environment.

6.2 Contributions of the *DESIGN ADVISOR*

The contributions of the *DESIGN ADVISOR* are:

- An efficient organization of manufacturing processes information in terms of manufacturing process characteristics such as process description, material utilization, flexibility, cycle time, operating costs, quality, shapes, typical products, common materials used, advantages, disadvantages, and geometric design rules
- An efficient organization of materials information in terms of material characteristics such as mechanical, properties, electrical properties, thermal properties, environmental properties, cost, manufacturability, and typical uses.
- Data sheets that provide specific numerical values of some important material

properties.

- Tables 2.1, 2.2, and 2.3 which rationalize the selection criteria that have been used to obtain candidate manufacturing processes and candidate materials.
- Figures of merit that qualify the suitability of candidate manufacturing processes and candidate materials.

6.3 Future scope of the *DESIGN ADVISOR*

While the *DESIGN ADVISOR* has a representative number of manufacturing processes and engineering materials that are currently being used, it does not cover all manufacturing processes or materials in use. However, its flexible design makes it a simple task to add information and data about other manufacturing processes and materials.

The number of manufacturing processes and materials selection attributes have been restricted to seven and eleven, respectively, because it is easy for a user to select too many conflicting properties, resulting in a null solution set. However, the number of selection attributes can be increased easily in the following way. The most important selection attributes can be used to obtain an initial solution set. The successful candidate manufacturing processes and materials can then be analyzed using a second set of less critical selection attributes. A systematic reduction of the solution space can help in selecting the most suitable materials and manufacturing processes without losing any good solutions at an early stage in the sorting process.

Most marketed products are comprised of more than one part. Each individual part will have to undergo a design, materials selection and manufacturing process selection optimization. However, it is often the case that the locally optimum manufacturing processes and materials are not compatible with each other. The *DESIGN ADVISOR* can be used to analyze a number of parts and then choose the most compatible solutions. The compatibility of these solutions can be based on either the total manufacturing time of the final product, the cost of the final product or some combination of them.

`In conclusion, the *DESIGN ADVISOR* as presently constructed is an extremely useful tool. Upon further modification it can be extended to perform a number of desirable tasks and can serve as the building block to a more comprehensive product development tool.

APPENDIX A

MANUFACTURING PROCESS SELECTION

A.1 Casting - Permanent Mold

A.1.1 Pressure Die Casting

Process description: Molten metal is injected under pressure into a permanent metal mold which has water-cooling channels. When the metal solidifies, the die halves open and the casting is ejected. (The process is similar to plastic injection molding.) In the cold-chamber process, molten metal is poured into the injection cylinder, but the shot chamber is not heated. In general, the hot chamber method is suited primarily for the casting of alloys having melting temperatures in the neighborhood of 1400 °F (700 °C) or less and which do not have an affinity for iron. The cold-chamber method is used for handling alloys having higher melting points approaching 1800-1900 °F (1000-1060°C), for alloys that have an affinity for iron such as aluminum, and for the casting of parts that require the highest possible density. See Figure E.1.

Materials utilization: Pressure die casting is a near net shape process. There is some scrap in the form of spurs, runners and flash, but these can be easily recycled. Therefore, the process has an excellent material utilization rating.

Flexibility: The tooling is dedicated and therefore the flexibility of the process is limited by the machine setup time.

Cycle time: Production rate is less than 200 pieces/hr, and less than 40 pieces/hr if pore free die casting is used. The solidification time is typically less than 1 s. Therefore, the cycle time is basically controlled by the time taken to fill the mold and remove the casting.

Operating costs: The die and equipment cost is high, and the labor cost varies from low to medium. Pressure die casting is most advantageous at high production rates, because the substantial equipment/tooling costs can be amortized at high production levels. Required number of products to justify use of process is in excess of 10,000, and can go as high as 100,000. The lower the temperature of the molten metal, the longer the die life and the more the number of parts that can be cast.

Quality: Pressure die casting can produce good surface texture, but turbulence while filling the mold produces a high degree of internal porosity. Typical surface roughness values are in the range 16-63 μinches (0.4-1.6 μm).

Shapes: Pressure die casting does not allow the use of complex cores, but can be used for either 2D or 3D contoured surfaces. Intricate shapes and details can be incorporated. It can be used to process a flat surface with a deviation from flatness of 0.013 in/ft (1.1 mm/m). The maximum area that can be manufactured is 1080 in^2 (0.7 m^2). Minimum section thickness for die casting is between 1 to 2 inches (25-50 mm). The normal dimensional accuracy is 0.004 in/in (± 4 mm/m). If undercuts are required, then the dies are considerably more costly. Pressure die casting can be used for round and non-round holes. The maximum depth to width ratio is 1:1 for blind holes and 4:1 for through holes. The minimum width of the work piece that can be manufactured using pressure die casting is 0.06 in (1.5 mm) for ferrous materials and 0.087 in (2.2 mm) for non-ferrous materials. Pressure die casting can be used to manufacture hollow shapes also. The maximum economical size for an aluminum work piece is 100 lb. (45 kg), and somewhat smaller for other materials.

Products: Pressure die casting is used to manufacture intricately shaped parts for automobiles, appliances, outboard motors, hand tools, hardware, business machines, optical equipment, and toys.

Materials: Die casting allows the use of a wide range of materials, including high melting point metals. Although lead and tin alloys cast well, they are seldom used as they find no applications in machines and appliances. Materials that are either seldom or never used are iron, carbon steel, nickel alloys, titanium and precious metals. Light alloys are the preferred materials because of their high fluidity and low melting temperature. The hot chamber method is restricted to very low melting temperature alloys like magnesium and zinc. Zinc alloys are die cast at 750-800 °F (400-425 °C) and find maximum use in cases where minimum weight and high-temperatures are not important factors. Use of these alloy castings above 300 °F (150 °C) is not recommended. Aluminum alloys and magnesium alloys and copper alloys (in that order) have higher melting points than zinc alloys and are, therefore, more expensive to cast. Aluminum and magnesium alloys are very stable and are selected either for low weight applications, when the temperatures exceed 300 °F (150 °C), or for corrosion resistance. Copper alloys offer maximum strength to the parts but have high melting points. The die life is short and the surface quality of the castings is not as good as with the other alloys used. Castings with thin walls are the most economical to cast. They are used where strength, hardness or corrosion resistance are important in the design. Silicon bronzes are used especially when thin sections are used, but are strength-wise not as good as aluminum bronzes or other bronzes.

Advantages: High production rates are achievable with castings of smooth surface and excellent dimensional accuracy.

Disadvantages: Pressure die casting required large investment for equipment and tooling. The process is normally suited to metals with lower melting temperature. The size of the casting is limited.

Design rules: See Appendix D.1

A.1.2 Centrifugal Casting

Process description: Molten metal is introduced into a sand or copper lined cylindrical steel mold, which is rotated about its long axis. The centrifugal forces press the molten metal against the mold walls, and cavities. See Figure E.2.

Materials utilization: Since no runners, risers, etc. are used in the process, there is a near 100% material utilization.

Flexibility: Spinning equipment is required. However the time to set up the equipment is relatively short.

Cycle time: Production rate is less than 50 pieces/hr. The cycle time is governed by the rate of introduction of the molten metal into the mold, as well as the rate of solidification of the metal. In the cases where sand lined molds are used, the solidification time is a lot longer and the cycle time is increased.

Operating costs: The die costs are medium, the equipment cost high, and the labor cost varies from low to medium. Equipment is not expensive, and with sand molds the process is competitive for small quantities. Metal or graphite molds require a moderate production quantity to be cost effective.

Quality: If the inner surface finish is not important, centrifugal casting is used. This is because porosity and non-metallic inclusions migrate towards the inner surface due to their lower density. However the outer surface has a good finish and the product has good dimensional tolerances. Typical surface roughness values range from 250 μinches (6.25 μm) upwards when sand molds are used and are below 250 μinches (6.25 μm) when permanent molds are used.

Shapes: This process is useful for casting cylindrical parts, especially if they are long, hollow and need no cores. Except for small parts, the number of intricate shapes that can be cast is limited. Cylinders from 0.5 inches (13 mm) to 10 ft (3 m) in diameter with lengths to 52 ft (16 m) have been cast. Wall thickness of the cast parts range from 0.2-5 inches (6-125 mm). Tolerances are comparable to those required for sand mold or permanent mold castings, depending on the centrifugal mold used.

Products: Typical parts made by centrifugal casting are: large rolls, gas and water pipes, engine-cylinder liners, wheels, nozzles, bushings, bearing rings, gears, etc.

Materials: Frequently used materials in centrifugal casting are iron, carbon steel, alloy steel, aluminum alloys, copper alloys and nickel alloys. Those that are either seldom or never used are stainless steel, tool steel, magnesium alloys, zinc alloys, tin alloys, lead, titanium and precious metals. Basically, all metals, excluding refractory and reactive metals, can be used. Alloys with high amounts of phosphorus are undesirable.

Advantage: Useful for casting cylindrical parts, especially if they are long. Process is applicable to all sand-cast metals.

Disadvantage: Except for small intricate parts, shapes that can be cast are limited. Spinning equipment is required and can be expensive.

A.1.3 Compression Molding

Process description: A molding material, usually preformed, is manually placed between mold halves, which are heated and closed under pressure. The material then flows to fill the mold cavity, polymerizes from the heat and hardens. The mold opens and the part is ejected or removed. No sprue, gates or runners are required. The material used by the process must be measured accurately to avoid excess flash and maintain uniform size within the mold. Metallic inserts may be molded into the product. Presses typically utilize hydraulic rams to produce sufficient force during molding. The factor limiting maximum size of the product is the press size. The main parts of the presses are the plunger and the mold. The different types of molds that can be used are: (a) flask type molds, which produce horizontal flash and require accurate charge of the plastic materials; (b) straight type plunger molds, which produce vertical flash, but allow inaccuracy in the charge of the plastic materials; and (c) landed plunger type, which produces no flash and must have an accurate charge of the plastic materials. See Figure E.3.

Materials utilization: The process has a high material utilization rating. The scrap consists of only flash. Sprues, runners are absent in this process. However, the flash is not recyclable in the case of thermosets and, therefore, there is a small amount of waste.

Flexibility: The process uses dedicated tooling. The time taken to change the molds is rather fast and the changeover time is dictated by the time it takes to preheat the mold.

Cycle time: The process cycle time is limited by the rate of heat transfer, and in thermosets, by the rate of the reaction of the polymer. Multiple cavity molds can be used to increase the production rate and reduce the cycle time. The solidification time is determined by the time taken for the polymer to react, and decreases as the temperature of the material increases. Production runs for compression molding varies from 1,000 to 1,000,000 pieces. Material handling is more time consuming because each cavity is usually loaded individually.

Operating costs: When thermosets are used mold costs are high, since the molds must withstand the molding pressures and temperatures. Molding cycles are longer than with injection molding, but the cost of the finished parts is low. When rubber is used the equipment is not highly complex and the cost of parts is reasonable, especially for moderate quantities. However, machine and tooling costs are low when compared to most other permanent mold casting processes.

Quality: The surface finish of the product is very good and its dimensional accuracy is good. The tolerances vary with material, nominal part dimensions and processing conditions. Problems that can occur include premature chemical reaction of the thermosets, air entrapment and inadequate filling of the cavity. Typical tolerances are ±0.04 in/ft (± 3.6 mm/m). The uniformity of the product, however, is highly operator dependent.

Shapes: Intricate shapes with side draws and undercuts are difficult to produce by this process because of the short flow lengths in the molds. Re-entrant angles are, however, possible in materials that are flexible at demolding temperatures. Thermoset parts can be intricate and have undercuts, although these are more costly. Sizes range from that of miniature electronic components to large appliance housings. Rubber parts as small as miniature pads for instrument components and as large as tires for large mining trucks can be produced. Parts can be irregular, but normally they are not highly intricate. Tolerances vary with the size, material and processing conditions. Typical tolerances are ±0.02 inches (±0.5 mm). It is possible to manufacture parts with controlled wall thickness, molded-in holes and threads. It is not possible to manufacture enclosed hollow shapes and large enclosed volumes.

Products: The most common products made by compression molding with thermosets are electrical and electronic components, dishes, washing machines, agitators, utensil handles, container caps, knobs and buttons used in higher-temperature environments. Typical rubber products are cushioned and anti-skid mounting pads, gaskets and seals, tires and diaphragms.

Materials: Typical thermosetting plastics are: alkyds (DAP and DAIP), aminos (urea and melamine), epoxides, phenolics, polyesters, polyamides, polyurethane's and silicones. Rubber is also commonly used. More recently, the process is being used to manufacture polymer-matrix composites.

Advantages: Tooling is relatively inexpensive, the process produces fewer flow lines and lower internal stresses. Since there are no runners, gating and sprues these potential waste by-products are eliminated, which is advantageous when thermosets are used since they cannot be recycled. There is a lower and more uniform shrinkage rate in compression molding. It allows molding of thin walled parts with a minimum amount of warpage and dimensional deviation.

Disadvantages: Intricate shapes with side draws and undercuts are difficult to produce. Phenolic, the common material for this process, has limited molded-in color choice. Larger parts take longer to cure than in transfer or injection molding. Material handling is more time consuming as each cavity is usually loaded individually. Also, close tolerances are difficult to achieve.

Design rules: See Appendix D.2.

A.1.4 Injection Molding

Process description: Injection molding is a near net shape process in which thermoplastic material is fed by gravity through a hopper into a heated barrel, where it melts and mixes. The material is then forced into a mold cavity through a gate and runner system, where it cools and hardens to the configuration of the cavity. Since the mold is kept cold, the plastic solidifies almost as soon as the mold is filled. Molds can be designed either for a single or for multiple parts. Once the product's material is chosen and the corresponding mold manufactured, the material cannot be changed because the shrinkage rates of different materials differ. Heavy clamping forces are necessary to keep the mold sections together to prevent the plastic from escaping under the high injection pressures. The cavity can produce either a solid or open-ended shape. The injection molding machine uses either a ram or screw-type plunger to force the molten plastic material into the mold cavity. In many products the injection molding process produces a parting line, sprue and gate marks and ejector pin marks. After release from the mold the finished parts are trimmed and are ready for immediate use. Machines are rated according to the weight of material displaced in one stroke of the plunger. Almost all machines are operated on an automatic cycle. Injection molding is used to produce more thermoplastic products than any other process. In some cases thermosets can also be used. See Figure E.4.

Materials utilization: The material utilization of the process is high. However, there is some scrap in the form of runners and sprues. Thermoplastic scrap can be recycled with a small amount of degradation in the properties of the molded materials.

Flexibility: The process flexibility is restricted by mold changeover and the machine setup time. Depending on the new product material and any color changes in the product, changeover time can be very large and costly.

Cycle time: The production rate of injection molding is fast, with typical product runs varying from 10,000 to 10,000,000 parts. The cycle time is limited by the solidification time and the demolding time. These are affected by the cooling channels provided around the mold and the size of the part.

Operating costs: At high production rates the process can be very economical. In addition, no secondary machining operations are needed. However, equipment and tooling costs are high and mold costs are very high.

Quality: The quality of the products that can be manufactured using injection molding can be very good, but it is sometimes sacrificed to attain high production rates. Pebbled-like and rough surfaces can be made with injection molding. These surfaces are used to mask scratches. Typical tolerances are ±0.008 inches (±0.2 mm) for thermoplastics and ±0.002 inches (±0.05 mm) for thermosets.

Shapes: Complex shapes are possible. Part sizes vary between 2-20 inches (0.05-0.5 m) in length or width and 2-15 inches (0.05-0.4 m) in depth. Small re-entrant angles are possible if the material is flexible.

Products: Typical products made by injection molding are containers of all type, covers, knobs, tool handles, plumbing, fittings and lenses.

Materials: Typical materials used by injection molding are epoxy, nylon, polyethylene, rubber and polystyrene. Recently, composites are being used increasingly in this process.

Advantages: The major advantages of injection molding are rapid production rates, intricate parts, molded-in color and finished part. Millions of parts can be manufactured with virtually no mold wear. Thermoplastic parts do not need deflashing.

Disadvantages: The major disadvantages of injection molding are that tooling is costly, large parts are not possible and small quantities are not economical. Thermoset parts need deflashing. Large clamping forces are needed to prevent the mold from flashing.

Design rules: See Appendix D.2.

A.2 Casting - Permanent Pattern

A.2.1 Sand Casting

Process description: A mixture of sand, clay binder and other materials is packed around a wood or metal pattern with cores to form a mold. The pattern is removed and the cavity left by it is filled with molten metal. Normally the mold is in two halves, which are fitted together before pouring. Cored sand casting is a process that involves the assembly of various mold sections and cores (made of sand or composites) to form a casting mold. With cored sand casting, shapes not obtainable through other casting processed can be produced. The design of the running and gating systems have helped reduce problems related to turbulence while pouring. A process known as the Cosworth process is used to make precision castings. This method uses a technique known as "upward filling," which helps to remove the impurities in the molten metal. See Figure E.5.

Materials utilization: Up to 50% of the molten metal used goes to form the sprues, runners and risers. Both the mold and scrap metal can be remelted and used again. However, due to the amount of scrap produced per cycle, the material utilization rating for this process is poor. Recycling sand molds helps reduce the costs for large production volumes, however, this can be difficult since removal of binders and hardening agents is costly.

Flexibility: Patterns are cheap and easy to make, and the process is very flexible.

Cycle time: The cycle time is limited by the rate of heat transfer through the casting and the mold. The use of multiple molds can increase production rates and decrease the cycle time. Typical production rates are less than 20 pieces/hr. The number of parts range for a production run range from 10 to 100,000.

Operating Costs: The cost of dies and equipment is low, and the labor cost varies from low to medium. Pricing is, in part, weight-based.

Quality: The surface texture of sand cast parts is poor. Porosity cannot be avoided and it is difficult to eliminate non-metallic inclusions from the work piece. Surfaces are irregular and grainy with average surface roughness varying from 500-1000 μinches (12-25 μm).

Shapes: Complex pieces such as engine blocks can be manufactured using sand casting. Cores can have match points built into them to aid in their alignment. Undercuts are possible with mold cores. Parts can weigh as little as 0.07 lb. (30 gm) or as large as 200 tons (182 metric tons), with sizes ranging to 120×120 in (3×3 m). Deviation from flatness is typically 4.2×10^{-3} inches/inch (4.2 mm/m). Intricate shapes with undercuts, reentrant angles and complex contours are practicable to cast, as are 2D and 3D contoured surfaces and hollow shapes. Typical dimensional accuracy is ±0.016 inches/inch (±0.016 mm/mm). Normal dimensional accuracy is ±0.06 inches (±1.5 mm) for holes 3 inches (75 mm) in diameter. The minimum practical cast hole diameter varies from 0.5-1 inches (13-25 mm) and requires a draft angle. The maximum depth to width ratio is 1.5:1 and also requires a draft angle. Minimum wall thickness should be greater than 0.25 inches (6 mm).

Products: Typical products made by casting are engine blocks, machine frames, compressor and pump housings, valves, pipe fitting, brake drums, etc.

Materials: Most frequently used sand casting materials are iron, carbon steel, alloy steel, stainless steel, aluminum alloys, brass, copper alloys, magnesium alloys and nickel alloys. Those that are sometimes used are tool steels, zinc alloys, tin alloys and lead. Those that are either seldom or never used are titanium and precious metals. All metals, except refractory and reactive alloys (like those of titanium), can be used.

Advantages: Intricate shapes, wide range of sizes and most metals can be used. Process can obtain shapes not attainable through other casting processes, and can be used for low production run products. Unit cost is low.

Disadvantages: Surface finish and dimensional accuracy poor, and secondary operations are needed in many cases.

Design rules: See Appendix D.1

A.2.2 Shell Mold Casting

Process description: A process in which molten metal is poured into a heat-cured, non-reusable shell mold made from silica sand on a resin binder and held until solidification of the molten metal occurs. Sand mixed with a thermosetting-plastic resin is poured onto a heated metal pattern. Metal patterns are tightly toleranced, have a smooth surface finish and are in two halves with sprue, gates and runners. They may not have undercuts, but, otherwise, can have very complex shapes. Upon the application of heat the sand mixture adjacent to the pattern fuses together, forming a shell that is removed from the pattern. Metal is poured into two shell halves fastened together. The shell is broken from the finished casting. Shell halves are clamped or bonded together, and the mold is placed in a flask and surrounded with shot, sand or gravel. This backing material reinforces the mold during the casting process. Metals cool rapidly. See Figure E.6.

Material utilization: The process uses non-reusable molds having runners, gates, sprues etc. Therefore the process has a poor material utilization rating.

Flexibility: Since a shell mold making machine is used, the process is not very flexible.

Cycle time: Production rates are typically less than 50 pieces/hr. Production volumes vary from 1,000 to 100,000 parts.

Operating costs: Since tooling costs are higher, this process is used for high production volumes. The least economical quantity that can be produced is around 500. Sand cost is higher than for other processes due to the use of resin. While tooling cost is high, the die cost is low to medium. This is because the shell mold making equipment is costly. The labor cost is low to medium.

Quality: Fine-grained, strong castings with good surface finish and dimensional accuracy are obtained. This process is superior to other sand casting processes, and provides an accurate duplication of intricate shapes with high dimensional accuracy. Surface finishes on the order of 63-500 μinches (1.6-12.5 μm) are feasible.

Shapes: Parts can be as heavy as 220 lb. (100 kg), but weights are normally less than 20 lb. (10 kg). Shapes can be complex with bosses, undercuts, holes and inserts. Cores are used to produce holes and cavities. Section thickness of as small as 0.1-0.25 inches (2-6 mm) are feasible. Tolerances of 0.005 inches/inch (5 mm/m) are recommended.

Products: Typical products made by this process are connecting rods, lever arms, gear housing, cylinder heads, support frames, etc.

Materials: Many metals, metal alloys and non-ferrous alloys can be cast. The most common metals are iron and steel.

Advantages: Best for high production runs. Provides good surface finish and dimensional accuracy. Cleaning is considerably reduced. The cured resins are not hygroscope, and can be stored for prolonged periods.

Disadvantages: Limited casting size. Equipment and tooling require a large investment. Resin also adds to the cost. Not all metals can be cast. Since the molds cannot be reused, the cost increases.

Design rules: See Appendix D.1

A.3 Casting - Expendable Pattern

A.3.1 Investment Casting

Process description: Wax is injected into a metal die. The patterns are then gated to a sprue to form a cluster. Multiple pattern clusters are used to increase the production rate. This is dipped into a slurry of refractory particles and dried until the required shell thickness is achieved. After the slurry sets, the mold is baked at high temperatures to remove the wax pattern. The resulting ceramic mold is now ready for the pouring of the casting material. Molten metal is poured into the ceramic mold, which has been preheated, thereby producing a casting. Pressure, vacuum or centrifugal force is used to fill the cavity completely. The thin refractory mold material is removed by either chipping or sand blasting. The gating is removed from the casting by cutting and then grinding. The casting itself can have intricate internal and external features with little or no draft angles. Investment casting is a process used for metals that melt at temperatures too high for metal molds. See Figure E.7.

Material utilization: The process is a near net shape process with little material lost in the feeding systems. The wax can be recycled easily. Therefore the process has high material utilization.

Flexibility: The flexibility of the process is good because of the ease with which the patterns can be produced.

Cycle time: The cycle time is limited by the rate of heat transfer out of the casting. Production rates are low because of the complexity of the process. The production rate can be increased and cycle time lowered by using cluster molds and patterns. Production rates are typically less than 1000 pieces per hour. The total number of parts per run range from 100 to 100,000, with 50 parts being the smallest number of parts for the run to be economical.

Operating costs: The equipment costs can be high if reactive alloys are used. The labor costs are high due to the many stages in the process. The main cost savings come from the elimination of further machining. Otherwise, this is a costlier process than other casting processes. It is most economical for low and medium production quantities.

Quality: There are no parting lines, and the product is a single piece that can have complex shapes. Excellent dimensional tolerance and surface finish are obtained. Higher mold temperatures decrease the porosity of the part, but may produce coarse microstructures. Care must be taken when making the patterns to account for shrinkage during cooling and solidification. Surface finishes range from 63-125 µinches (1.6-3.2 µm).

Shapes: Part size is normally small, but can range in weight from 0.002-80 lb. (0.001-35 kg). Minimum wall thickness can varies from 0.03-0.07 inches (0.75-1.8 mm).

Tolerances vary from ±0.03-0.06 inches (±0.8-1.5 mm). Shapes can be very intricate with contours, undercuts, bosses, recesses, etc.

Products: Typical parts made by this process are precision parts for sewing machines, typewriters, firearms, surgical and dental devices, wrench sockets, pawls, cams, gears, turbine blades, valve bodies, radar wave guides, etc.

Materials: This process is suitable for almost all metals. Reactive metals can be cast under a vacuum. The most commonly used materials are carbon steel, alloy steel, stainless steel, tool steel, aluminum-copper-nickel alloys. Aluminum, cast iron, magnesium are very suitable because of their high fluidity due to silicon additives. Cast steels and brass can also be used. Sometimes magnesium alloys and precious metals are used, but iron, zinc and tin alloys, lead, and titanium are either seldom or never used.

Advantages: Almost all metals can be cast with high dimensional accuracy, smooth finishes, and intricate shapes. Although a small draft is advisable, investment cast parts do not necessarily require drafts.

Disadvantages: It is most suitable for smaller parts, and is justifiable only when secondary operations can be eliminated. Labor costs are high and patterns may be expensive.

A.4 Cutting - Mechanical Machining

A.4.1 Single Point Cutting

Process description - turning and facing: A material removal process using a single point cutting tool whose major motion is parallel to the axis of rotation of the work piece. Facing is a special case in which the major motion is perpendicular to the axis of rotation.

Turning produces cylindrical external surfaces, whereas during facing flat surfaces perpendicular to the axis of rotation are produced. The single point tool produces fine helical marks on the cylindrical surfaces that are a function of the tool's feed rate. The work piece is held in a chuck and the tool is mounted on a tool post. Chips result from the cutting and chip removal can be a problem. The dimensional accuracy and surface finish are affected by tool geometry, cutting speed and feed rate, rigidity of the tool, work piece and machine, alignment of machine components and fixtures, and cutting fluids. The cutting fluids are used to lubricate and cool simultaneously, which, in turn, reduces tool wear, allows high cutting speeds and feed rates, flushes chips, prevents rust and prevents a built-up edge on the cutting tool. Straight cylinders, tapered cylinders and any combination of these can be obtained. Turning creates residual surface stresses, may create microcracks and may cause surface or work hardening on unhardened materials. See Figure E.8.

Process description - boring: Boring is used to produce an accurate internal cylindrical surface by enlarging an existing opening in the work piece. The work piece moves parallel to the axis of rotation of the cutting tool. The process leaves helical feed marks as either the work piece or boring bar advances. The bored hole is always concentric with the axis of rotation of the tool. Vertical boring is used on large work pieces in which the work piece rotates about a vertical axis and the cutting tool is fed into the work. Vertical boring is used on parts that have a small length to diameter ratio, as these parts are difficult to hold and rotate on a horizontal axis lathe. Boring has the same effects on the mechanical properties of the work piece as turning. Typical bore diameters range from 24-200 inches

(0.6-5 m) and depths from 36-72 inches (0.9-1.8 m). The maximum depth to diameter ratio is 5:1. Tolerances and surface finishes are similar to those in turning.

Materials utilization: Material utilization is extremely poor in turning and boring. The scrap that is produced during machining is expensive to recycle due to the contamination of the lubricant and the changes in the microstructure as a result of the chip creation process.

Flexibility: The flexibility of this process is extremely high. It is ideal for the production of individual pieces and very small batches.

Cycle time: The cycle time is controlled by the relative hardness of the work piece and the tool. The cycle time can be reduced somewhat by using automation. A typical material removal rate is 1.3 in^3/min (21 cm^3/min).

Operating costs: Tooling is not dedicated and the machine costs depend on the degree of flexibility and automation selected. The operating costs can range from low to very high depending on the type of machine used.

Quality: Turning is often used to improve the surface texture, and is only limited by the time and the effort expended. Tolerances in both length and diameter are ±0.001 inches (±0.025 mm) for most applications and for precision applications ±0.0002 inches (±0.005 mm) for diameter and ±0.0005 inches (±0.0127 mm) for length. Typical surface finishes vary over the range 16-125 μinches (0.4-3.2 μm).

Shape: Geometric possibilities within the cylindrical geometry's are plains and faces, tapers, contours, radii, fillets and chamfers.

Products: Typical products made by turning are rollers, pistons, pins, shafts, rivets, valves, tubing and pipe fittings.

Materials: Aluminum, brass and plastics have excellent machinability ratings, cast iron and mild steel have good machinability ratings. Stainless steel has a poor to fair machinability rating because it is tough and it work hardens.

Design rules: See Appendix D.3

A.4.2 Milling (Multiple Point Cutting)

Process description: Milling is a cutting process in which material is removed by a rotating multiple-tooth cutter. Arbor milling is a form of milling in which the cutting takes place on a surface parallel to the axis of the tool rotation; for end milling the axis of the tool rotation is perpendicular to the cutting surface. The discontinuous chips that are formed during milling are, for the most part, swept away by the rotation of the cutter. Either the work piece may be fed into the cutter or the cutter may be fed into the work piece. In conventional milling (up milling) the direction of rotation of the cutter is opposite to that of the work piece feed direction. In climb milling (down milling) the direction of rotation of the cutter and the work piece feed direction are the same. Milling is most efficient when the work piece hardness is less than Rockwell C25. A large number of different milling cutters can be used to obtain different shapes. See Figure E.9.

Mechanical properties: Work piece properties change due to milling. A built up edge on the cutter causes a rough work piece surface. Dull tools cause severe surface damage and high residual stresses. An untempered martensitic layer about 0.001 inches deep (25.4

μm) may be produced while milling heat treated alloy steels.

Materials utilization: Material utilization in milling is extremely poor. Scrap is difficult and expensive to recycle due to contamination by the lubricant and changes in the microstructure of the scrap material.

Flexibility: The flexibility rating of milling is high. It is ideal for the production of individual articles and small batches.

Cycle time: The cycle time is controlled by the relative hardness between the tool an the work piece, the lubrication and the rate of cooling. The cycle time can be reduced with automation. Material removal rates with mild steel can be as high as 365 in^3/min (6000 cm^3/min).

Operating costs: There is little dedicated tooling in milling. Machine costs depend on the degree of flexibility and automation. Operating costs are relatively low.

Quality: Milling can be used to improve the surface quality, and is only limited by the time and effort expended. Typical surfaces finishes range from 63-200 μinches (1.6-5.0 μm). Typical deviation from flatness is ±0.005 in/ft (0.4 mm/m).

Shapes: Flat, convex and concave surfaces and 3-D contoured surfaces can be milled. Typical tolerances are ±0.005 inches (±127 μm).

Products: Milling is used in the generation of simple to complex 3D shapes over a very wide range of part dimensions.

Materials: Aluminum, brass and plastics have good to excellent machinability, cast iron and mild steel have good machinability and stainless steel has fair machinability (due to work hardening). Polymers, some ceramics and composites can also be milled, although the tool wear rates can be high when machining ceramics and composites.

Design Rules: See Appendix D.4

A.4.3 Grinding

Process description - cylindrical grinding: Grinding is a process that removes material from a work piece using a tool made from abrasive particles of irregular geometry embedded on the surface of a rotating wheel. The process produces straight, tapered and formed work pieces. To produce tapers either the wheel or the table are swiveled. For cylindrical work pieces the work piece is mounted between centers, with the work piece and grinding wheel rotating in opposite directions. The grinding process produces highly accurate surfaces with smooth finishes, and has less vibration than other material removal processes. The geometry of the work piece is a mirror image of the grinding wheel. When the wheel is a formed wheel, the process is called plunge grinding. Wheels are usually 45% abrasive, 15% bonding material and 40% porosity by volume. It is the porosity of the wheel that provides space for the chips and a path of delivery of the coolant. Grinding fluids are needed to cool the wheel and work piece, to lubricate the wheel and work piece interface and to aid in removing chips. See Figure E.10.

Process description - surface grinding: Surface grinding is essentially the same process as cylindrical grinding, except that it forms a flat surface. It sometimes used to finish a formed surface. A grinding wheel, a reciprocating table, work holding devices, such as a magnetic chuck for metallic work pieces and adhesive materials or vacuum chuck for non-metallic materials, constitute the basic equipment required. The wheel spindle can be either vertical or horizontal.

Mechanical properties: The grinding process creates residual surface stresses and a thin martensitic layer on the surface due to the high temperatures generated. Because of these two factors fatigue strength may be reduced. It can also cause a loss of the magnetic properties of ferromagnetic materials, and may increase a material's susceptibility to corrosion.

Materials utilization: Material utilization is extremely poor in grinding. The scrap produced is difficult and expensive to recycle due to lubricant contamination and changes in its microstructure. In fact, the scrap produced gets into the grinding wheel and causes "loading" of the wheel, which greatly reduces its the cutting efficiency. As soon as the wheel is loaded, it must be redressed; i.e., the loaded surface layer must be removed and fresh cutting particles exposed.

Flexibility: Grinding has a high flexibility rating. The form grinding tooling can be expensive.

Cycle time: The cycle time is relatively slow and is affected by the relative hardness of the work piece and the tool, the lubrication and the amount of cooling. The cycle time can be reduced by increasing the degree of automation.

Operating costs: Some of the tooling in grinding is dedicated. The machine cost depends on the degree of flexibility and automation. Grinding is a process that consumes a lot of power for the following two reasons. (1) Each cutting particle is small and therefore cuts only a small area of the surface. The area around the groove cut by the abrasive particle forms a raised edge which is removed by the following particles. This "ploughing" mechanism is an inefficient method of removing material. (2) The cutting particles are randomly oriented and have no uniform geometry; thus, there is no optimization of the equivalent of a tool's rake angle. Some particles will be shaped and oriented so that they do not cut at all and just rub the surface. This also leads to higher power consumption.

Quality: Grinding is basically a finishing process, and the surface quality obtained depends on the amount of time and effort expended. Typical values of surface finish range from 8-32 μinches (0.2-0.8 μm) and the typical tolerances are ±0.0005 inches (±12.7 μm) for diameters and ±0.0001 inches (2.5 μm) for roundness. For precision applications the tolerances can be as low as one-tenth these values. Material removal rate for mild steel are as high 10 in^3/min (165 cm^3/min). For surface grinding the tolerances for flatness are typically ±0.002 inches (±0.05 mm) and for parallelism ±0.003 inches (±0.075 mm). Deviations in flatness are typically ±0.001 inches/ft (±0.08 mm/m).

Shape: Cylindrical grinding produces straight, tapered and formed work pieces. Surface grinding is used for the grinding of flat and contoured surfaces and slots.

Products: Typical applications are to form shafts, pins and axles over a range of sizes: 0.75 to 20 inches (0.02-0.5 m) for diameters and 0.8 to 75 inches (0.02-2 m) for lengths.

Materials: Grinding can be used on all materials except those that become either soft or gummy. The best results are obtained with cast iron and mild steel, the next best with aluminum, brass and plastics and the poorest with stainless steels, because they are tough and tend to work harden. Ceramics can also be ground successfully.

Advantages: Excellent surface finishes can be obtained using grinding.

Disadvantages: High power consumption, low efficiency process with poor material utilization. The process creates residual surface stresses that reduce the fatigue strength of the work piece.

Design rules: See Appendix D.5

A.5 Cutting - Electromachining

A.5.1 Electric Discharge Machining (EDM)

Process description - wire cutting: A wire that move past the part is used as the tool to produce complex 2-D shapes. Typical diameters of the wires vary from 0.001-0.012 inches (0.025-0.3 mm). The wire is inexpensive and is, therefore, not usually not reused. Mirror image profile work and internal contours can be manufactured from a starting hole. Multiple work pieces can be stacked and cut, and the finished products do not contain burrs. See Figure E.11a.

Process description - cavity type: Cavity type EDM is a thermal mass reducing process that uses a shaped electrically conductive tool to remove electrically conductive material. This is done by means of thousands of controlled, repetitive spark discharges per second across a gap of approximately 0.001 inches (0.025 mm). These discharges cause the work piece to vaporize and slowly produce the desired shape. Burr-free finished parts are obtained. A dielectric fluid is used to flush the removed particles, to regulate the discharge, and to keep the tool and work piece cool. The dielectric is usually a hydrocarbon oil with the tool and work piece submerged in it. The dielectric is circulated by a pump and is recycled after the work piece particles have been filtered. A heat affected zone of approximately 0.01 inches (250 μm) thick is produced. In steel it produces a thin carbide layer, which lowers the fatigue strength and creates microcracks. The finish on the work piece is affected by the gap voltage, discharge current and supply frequency. The material removal rate is low and, therefore, for high production volumes EDM is basically used as a finishing process. See Figure E.11b.

Materials utilization: The material utilization rating is extremely poor for this process. The scrap that is generated due to the machining process cannot be recycled.

Flexibility: The tooling is dedicated in the EDM process. Set up times can be short and, therefore, the process has a high flexibility rating.

Cycle time: The cycle time is normally long for EDM. The rate of material removal depends on various work piece properties, including its melting point and its latent heat. The material removal rate is typically 3 in^3/hr (49 cm^3/hr).

Operating costs: The combination of the machines used and the setup required to obtain the operating conditions make this process expensive.

Quality: The surface texture is inversely proportional to the material removal rate. Surface finishes are in the range 50-150 μinches (1.3-3.8 μm), and tolerances range from ±0.00015- 0.0005 inches (± 4-13 μm) at very slow material removal rates.

Shapes and products: The method is often used for making dies for extrusion, powder metallurgy and injection molding. Frequently, punches and dies are manufactured using wire EDM.

Materials: All metals can be used in this process. All conducting non-metals can also be machined.

Advantages: Used in cases where the materials that have to be machined are harder than typical tool materials. The process has a high repeatability.

Disadvantages: Care however must be taken with some metals, as the surface has a heat affected zone, and in heat treatable metals this layer will be very hard. Minute cracks can appear if extra high amperage is used, which may result in premature fatigue failure. Sensitive tool steels may be damaged if very thin sections or sharp corners are used, unless a post tempering operation is employed to relieve stresses.

A.6 Forming - Sheet

A.6.1 Blow Molding

Process description: Hollow products are manufactured by extruding a heated (softened) thermoplastic tube (called a parison) into a mold, and, under air pressure, expanding the parison to match the inner contours of the mold. There it cools and hardens. The mold opens and the part is ejected. Parts are uniform in thickness. The process is limited to thin-walled hollow products. Parting lines and flash are present, but the flash is minimal. This process is suitable for the manufacture of thin-walled, hollow objects with internal volumes up to 55 gallons (0.2 m^3). The parts can have metal inserts. See Figure E.12.

Materials utilization: The process is a near net shape one if the parison that is used is produced by injection molding. There is some scrap if the parison is produced by extrusion. Therefore the material utilization rating of blow molding is high.

Flexibility: The tooling that is used in the process is dedicated. Setup times are relatively short.

Cycle time: The cycle time is limited by the heating and the cooling of the polymer used, but are considered relatively low. This time can be reduced by automating the process. The production volume for this process varies from 1,000 to 10,000,000 parts.

Operating costs: The tooling used in blow molding is relatively inexpensive. The machines are costly, particularly if the degree of automation is high. It is, however, the lowest-cost method of producing bottles and other closed containers at high production levels.

Quality: The surface texture that can be obtained using this process is good. However, significant molecular orientation may be induced. Both the surface finish and the dimensional accuracy are fair. Tolerances for this process vary from ±0.02-0.1 inches (±0.5-2.3 mm).

Shape: The process is limited to open and closed hollow products. Molded-in holes are not possible. However, products with intricate shapes and controlled wall thickness can be made.

Products: Typical products are bottles and other containers, hollow toys and decorative objects.

Materials: The work piece materials are thermoplastics, principally polyalkenes and PET. The use of thermosets is not possible.

Advantages: An economical process for rapid production of containers and other one-piece complex hollow products.

Disadvantages: Limited to hollow products and is not suitable for small quantities. Tolerances are relatively broad and wall thickness is difficult to control.

A.6.2 Sheet Metal Working

Process description - punching and blanking: Punching is a shearing process in which a scrap slug is separated from the work piece when the punch enters the die. This process is most economical for making holes in sheet metal for medium to high production rates. Blanking is a process in which the piece of sheet metal that is separated by the punch action is the required finished product, and the leftover sheet metal is the scrap. A punch mounted on a ram mates with a die mounted to the bolster plate. Multiple punches are often used to finish a part in one stroke. See Figure E.13.

Process description - perforating: Perforating is a punching process in which a desired pattern of holes is cut into the work piece by means of multiple punches and dies. The quality of the pierced hole is controlled by the punch and die clearance. Punches shear the waste from the work piece as they enter the dies. Work pieces have burnished and sheared areas on the side walls of holes. The process produces burrs on the bottom surface.

Materials utilization: Material utilization depends on the arrangement of the punches to minimize scrap. Material utilization can be increased by modifying the part's design to facilitate better nesting of the designs. There is always a minimal amount of scrap that is too expensive to recycle.

Flexibility: Tooling is dedicated, and the set up time depends on the tooling complexity. Therefore, the process has a low flexibility rating.

Cycle time: Relatively fast cycle times can be obtained, but depends on the number of punches used and the feed rate of the sheet metal strip.

Operating costs: Operating costs are determined by the complexity and the number of punches that are used. The amount of scrap will also determine the operating costs.

Quality: The process produces a burnished area, roll over and die break on the side wall of the resulting hole. Typical dimensional accuracy is ±0.006 inches (±0.15 mm) and typical surface finishes range from 32-63 μinches (0.8-1.6 μm).

Shapes: A large number of complicated shapes can be obtained by selecting the shapes of the punches. The only limitations that the part is of constant thickness.

Materials: Steel, aluminum, brass and stainless steels are the most commonly used materials. Low carbon steels and medium carbon steels are the best for stampings, but they must be low temper steels. Stainless steels can be worked much more severely than ordinary steels (when annealed) but require a much higher press power. Nickel alloys are similar to stainless steels. However, they appreciably work harden during punching and may have to be annealed if additional operations are required. Brasses and copper alloys form excellent stampings, but bronzes with lower ductility are not as desirable. The soft temper aluminum alloys are the most easily worked and are preferred when their strength is adequate. The less ductile heat-treated or age-hardened alloys can be used if properly worked. Magnesium alloys can be stamped at high temperatures (450-600 °F [230-315

°C]). The following materials can be punched or blanked and are ranked in decreasing order of blanking ease: lead, paper, leather, aluminum, zinc, cast iron, fiber, copper, German silver, brass, wrought iron, tin, low carbon steel, medium carbon steel, high carbon steel, untempered tool steel, nickel steels, tempered tool steels.

Advantages: There is reduced material handling, the process is automated and requires minimal supervision. A large number of shapes and sizes can be obtained. Surface finishes are good.

Disadvantages: A costly setup with a lot of scrap that cannot be recycled. One the die is built, changes are not possible or are very difficult. The process is restricted to thin sections.

Design Rules: See Appendix D.2

A.7 Forming - Bulk

A.7.1 Forging

Process description: Drop forging is a metal shaping process in which a heated work piece is forced to conform to the shape of a die cavity by rapidly closing a punch and die. The closing of die cavities may be either singular or repeated; typically, however, one blow is given in each die cavity. The drop hammer is powered by either air, hydraulic or mechanically. Striking forces from 11,000-425,000 lb. (50-2000 kN) are obtained, depending on the mass of the ram and upper die, and on the drop height. As the forging forces increase the dimensional tolerances improve. The product is usually manually loaded and removed. The resultant forging approximates the shape of the finished part, but secondary machining is usually required to obtain dimensional tolerances and good surface finish. The process produces a parting line and flash on the work piece, which must be removed. Parts can weigh from 3-750 lb. (1-350 kg) and overall dimensions can vary from 3-50 inches (0.1-1.3 m). If the preform mass is carefully controlled in closed die forging, it can be forged in totally enclosed dies with no flash gutters. When components are formed in closed dies with relatively little gross plastic deformation to produce the final size or detail, then the process is known as coining. See Figure E.14.

Open die forging is a process in which a solid work piece is placed between two flat dies and reduced in height by compressing it. The die surfaces in open die forging may have simple cavities to produce relatively simple shapes. Upset forging is a metal shaping process in which a heated work piece of uniform thickness is gripped between split female dies while a heading die (punch) is forced against the work piece, deforming and enlarging the end of the work piece. Open die forging is used for manufacturing large parts, while closed die forging is used to manufacture smaller components. Open die forging produces shapes like rings and shafts. Large components up to 300 tons (270 metric tons) can be forged economically this way. Upset forging is used to form bolts and to increase locally the cross sectional area of any component.

Mechanical properties: Forging creates good to excellent mechanical properties, including improved fatigue and impact resistance. However, the process may create microcracks.

Materials utilization: Hot forging in closed dies always produces scrap material in the form of flash. Cold forging can be a near net shape process. Cold forging has almost

100% material utilization; in hot forging it is lower.

Flexibility: Open die tooling is not dedicated, but is in closed die forging. The length of the set up period depends on the complexity of the tooling. The open die forging process has a good flexibility rating, while the cold die forging process has a poor flexibility rating.

Cycle time: The cycle time is dictated by the rate of operation of the equipment. Open die forging has longer cycle times, because of the large size of the parts that are manufactured. The cycle time in closed die forging can be quite short, depending on the degree of automation.

Operating costs: Tooling costs are moderate to high, depending on the part's complexity. There is a moderate material loss due to flash and secondary machining. Labor costs are moderate in closed die forging, while highly skilled operators are needed for open die forging. The degree of automation decides the cost in closed die forging. This process is economical for medium to high production levels.

Quality: The quality of the forged products depends primarily on the forging temperature. The surface texture and the dimensional tolerances deteriorate with increasing temperature. Therefore, cold forging has excellent quality rating, whereas hot forging results in products that have a poor surface finish and dimensional tolerance. Usually further machining is required. Parts produced by open die forging tend to develop a barrel shape. Barreling is caused primarily by frictional forces at the die and work piece interface, where the outward flow of material occurs. Barreling can be minimized by using an effective lubricant. Typical dimensional tolerances range from ±0.02-0.03 inches (±0.5-0.8 mm). Surface finishes range from 80-300 µinches (2-8 µm).

Shapes: The process can be used to produce 3D solid shapes without undercuts or re-entrant angles. Stock work pieces are round, square or flat with medium to high ductility. They are cut from a parent work piece to provide a favorable grain flow orientation.

Products: Forging is used to make mechanical parts that are subjected to high stresses in aircraft engines and structures, land based vehicles, portable equipment, connecting rods, crankshafts, valve bodies, gear blanks, etc.

Materials: Cold forging. As the carbon and alloy content of the steels increase, their forgeability decreases. Most non-ferrous metals such as copper, forging brass, naval brass, bronze, and copper alloys are easily forged. The materials are selected on a compromise basis. First the required strength and the physical properties must be met. Corrosion resistance, size, toughness, fatigue resistance, heat resistance, and section thickness must then be balanced against forgeability. Forgeability ratings for some commonly used metals are given based on the die life, in decreasing ease of forgeability: forging brass, forging copper, naval brass, alloy and low carbon steels (in increasing order of carbon/alloy content) and monel metal.

Hot forging. All metals that can be cold formed can be used for hot forming. Also, metals unsuitable for cold working can be hot forged. Although hot forgings are costlier than cold forging, in certain cases, as with silicon-aluminum-bronze, stronger parts result with few or no dangerous internal mechanical stresses. Nonferrous materials have a narrow temperature range in which they flow easily. Danger of overheating these metals is high and the process, therefore, must be precise. However, their high forgeability, corrosion resistance and color make them very useful. The relatively high forging temperature of copper, coupled with its tendency to form a black oxide, which has serious erosive action on dies, makes it better suited for cold forgings. Normalization of forged steel parts is necessary to obtain maximum grain refinement. It also improves machinability and relieves internal stresses created upon cooling. Normalization is a heat treatment process in which steel is heated to a temperature above its critical temperature, a temperature at which phase change occurs, and then cooled to below that range in air. Stainless steels and high carbon steels work similarly. At high temperatures, stainless steels are stronger and, therefore, are more difficult to forge.

Advantages: Controlled grain structure provides enhanced mechanical strength to forged parts. Forgings are light in weight per unit of strength. There is a low loss of material and few internal flaws in the finished product.

Disadvantages: Machining is required to provide accurate finished dimensions, otherwise tooling and processing costs become high.

Design Rules: See Appendix D.7

A.7.2 Rolling

Process description: A strip of sheet metal is fed continuously through a series of contoured rolls in tandem. As the stock passes through the rolls it is gradually formed into a shape with the desired cross section. The work piece is a coiled strip of ductile stock, which is then rolled into either simple, cylindrical or complex shapes varying in thickness from 0.004-0.125 inches (0.1-3 mm) thick and up to 20 inches (0.5 m) wide. Roll sets can also have side rolls. The size of the rolls depends on the work piece thickness and its formability. Rolling is a plane strain operation. By constraining the direction perpendicular to the direction of rolling the displacement (deformation) of the length of the work piece is increased, not its width. Therefore, as the work piece elongates during rolling it speeds up; that is, the work piece speed is slower than the rolls while entering them and faster than the rolls when exiting them. The frictional force acts at a central point, where work piece speed and roll speed are the same. Friction is necessary for rolling to occur, and the roll pressure depends on the coefficient of friction. See Figure E.15.

Material utilization: Scrap may be produced when the continuous product is cut to the proper length. The process has a high material utilization rating.

Flexibility: Most of the rolls are not dedicated. However, shaped rolls are dedicated and their setting up time is high. Therefore, the flexibility rating of rolling is fair.

Cycle time: The cycle time is dependent on the length of the product, but the production rate is rapid.

Operating costs: Production rates are rapid so that labor costs are low. Material utilization is excellent. Tooling and setup costs are high, so best economics occur with mass production.

Quality: The quality of the finished product depends primarily on the rolling temperature. The surface texture deteriorates with increasing temperature. Typical tolerances are ±0.015 inches (±0.4 mm) for the width of the formed cross section and ±0.060 inches (±1.5 mm) for its depth. The surface finish typically varies from ±10-150 μinches (0.25-3.8 μm) depending on the severity of the forming. It typically varies from 16-50 μinches

(0.4-1.3 μm) for cold finished sheet stock.

Shape: Finished part thickness ranges from 0.025-0.125 inches (0.6-3 mm). Parts are typically long with a constant cross section that can be complex. Short pieces can be obtained by cutting longer ones. Widths of the stock before forming normally range to 40 inches (1 m) and stock thickness to 0.2 inches (5 mm). The resulting product from rolling is suitable for both decorative and structural products.

Products: Products typically made by rolling are roof and siding panels for buildings, architectural trim, down spouts, window frames, stove and refrigerator panels and shelves, curtain rods, and metal picture frames.

Materials: Any metal that is ductile at the temperature of forming can be used. Aluminum, copper and their alloys have excellent formability ratings, nickel and magnesium have fair to good formability ratings and mild steel and stainless steel have fair to excellent formability ratings.

Advantages: The best applications are longer parts with complex cross sectional shapes. Production is rapid. Surface finish and dimensional consistency are good.

Disadvantage: Parts must have the same cross section for its entire length. Tooling and setup costs are high. The process may cause work hardening and microcracks. There is a tendency for the work piece to slip.

Design Rules: See Appendix D.8

A.7.3 Extrusion

Process description: Metal billets (slugs) are forced by either a mechanically or hydraulically actuated ram either through a die hole of the desired shape or around a punch. The metal emerges from the die in solidified form and closely conforms in cross section to the shape and dimensions of the die opening. The punch controls the inside shape of the work piece. The die controls the outside shape of work piece and may have more than one diameter. The work piece is ejected by either a counterpunch or an ejector. The rams are actuated between 20 to 60 times (strokes) per minute. Sometimes the punch and die has to be cooled by compressed air in order to maintain continuous production. This is because there can be significant temperature rise during cold forming, which can cause incipient melting (melting of the low melting point phases in the microstructure). There are three types of extrusion processes: (1) forward extrusion in which the metal flows out (downward) through die (see Figure E.16); (2) backward extrusion in which the metal flows (upward) around the punch (see Figure E.17); and (3) combined forwards/ backward extrusion (see Figure E.18). Forward extrusion can be used to produce complex shapes and reduces cross section of the work piece drastically. Backward extrusion cannot produce very long shapes, but can produce hollow components with large length to diameter ratios. Aluminum toothpaste tubes are manufactured this way. Wall thickness of the product is controlled by the clearance between punch and the die. The final work pieces have excellent surface finish. Round, cylindrical cross sectional parts are most common, but rectangular or odd cross sectional parts are also possible. Length of extruded part is limited by the column strength of the machine. Length of the finished part is limited to 6 times the inside diameter of the part.

Materials utilization: Extrusion is a near net shape process and the only scrap that is produced is during the cutting of the continuous product to its length. The material utilization rating of this process is high.

Flexibility: The tooling is dedicated and setting up times can be long. The process has a fair flexibility rating.

Cycle time: The cycle time is dependent on the product's length, but the production rate is very high and therefore the cycle time is low.

Operating costs: Hot extrusions need protection of the work piece from air and oxidation. Therefore, hot extrusion is a more expensive process. Cold extrusion has high tooling and setup costs; therefore, this process is best for mass production.

Quality: The quality of the product is generally good for all metals, but depends mainly on the forming temperature. The surface texture deteriorates with increasing temperature. Typical tolerances are ±0.010 inches (±0.25 mm) for diameters and ±0.015 inches (±0.4 mm) for lengths. Surface roughness typically ranges form 20-120 µinches (0.5-3.2 µm). The tolerances and surface roughness depend on press condition, ram pressure, tool geometry, material size and shape, allowed length-to-diameter ratio and lubrication, and whether or not hot or cold extrusion is used.

Shapes: Hot extrusions. Constant cross sections of any length up to 25 feet (7.5 m) are feasible. Cross sections can be large enough to occupy a circle 10 inches (250 mm) in diameter for aluminum and 6 inches (150 mm) in diameter for steel, and they can be very complex. Cold extrusions. The parts can range from 0.5-6.3 inches (12-160 mm) in diameter, and the maximum length of the part is 7 feet (2 m). This process is suitable for circular, hollow parts closed at one end. Cylindrical cross sectional parts are most common, however, rectangular or odd cross sectional parts are also possible. The work pieces can have either combined shapes, stepped shapes or cupped shapes. Typical work piece diameters are 0.5-20 inches (0.01-0.5 m) and typical work piece lengths range from 0.5-30 inches (0.01-0.8 m).

Products: Typical products made by extrusion are building and automotive trim, window frame members, tubing, aircraft structural parts, railings, furniture, flashlight cases, aerosol cans, military projectiles, fire extinguishers and collapsible tubes.

Materials: Hot extrusion. Most commercially available shapes are extruded in copper, brass, steel, aluminum, zinc, and magnesium. A large number of copper based alloys can also be extruded. Those with the highest zinc content are the most plastic and can produce the most complex shapes. Those with 56-63% copper require the lowest extrusion pressure. Hollow shapes cannot be made in steel, copper or copper alloys. Cost of extruding zinc alloys is higher than for the brasses and are, therefore, seldom used. As the copper content exceeds 63%, the alloys are more difficult to extrude. The lead content is also a factor, and high lead copper alloys are not used. In addition, phosphor bronzes, aluminum bronzes, and nickel silvers (nickel + copper = 60-63%) are also used. Cupro-nickel alloys (20-30% nickel), monel, K-monel and inconel have been hot extruded, but only for simple cross sections. Lightweight alloys, like those of aluminum and magnesium, are the most frequently used materials for extruded parts. Harder alloys are more difficult to extrude. Steels and stainless steels can also be extruded.

Cold extrusion. Most cold extrusions have used tin. The method has also been used on lead and aluminum parts. Zinc can be handled with a little preheating to get it to the ductile range (300 °F [150 °C]). Copper and brass can also be worked using the Hooker process, which can also be used on steels. In the Hooker process, a cold blank is introduced into a strongly supported cylinder containing a die bush. A punch is then made to enter the die, fitting it closely so as to prevent the escape of metal around its sides. The pressure exerted by the shoulder of the punch squeezes the blank, and then as the punch descends, causes it to extrude through the annulus formed by the projection of the punch and the die bush. The end result is a hollow tube. The strain hardening aluminum alloys are used only if strength requirements are moderate.

Advantages: Intricate cross sectional shapes, including undercuts and hollows, can be obtained. The tooling cost is low. Extrusion increases the hardness and yield strength of the material. High material utilization reduces wastage costs and, usually, further machining is not necessary.

Disadvantage: Limited to ductile materials and restricted to a maximum cross sectional size. Parts of non-uniform cross section require additional operations. Extrusion creates residual surface stresses and microcracks. Close tolerances are difficult to achieve.

Design Rules: See Appendix D.9

A.8 Powder Processing

A.8.1 Powder Metallurgy

Process description: Power metallurgy is a net-shape manufacturing process in which a metal power is compressed to a particular shape and then heated to bond the metal particles together. A powdered is compacted into the required form and part density by the action of opposing punches, which move in a die. The number of upper and lower punches depends on the complexity of the part. Compaction pressures may range anywhere up to 100,000 psi (70 MPa). After compaction, a part is sintered by placing it on a conveyor and slowly passing it through a furnace. Sintering, which takes place below the melting temperature of the primary constituent of the power, causes the power particles to bond together to produce the required properties of the part. See Figure E 19.

Material utilization: The process is near net shape and the material utilization is almost 100%.

Flexibility: The tooling expenses are moderate and equipment is fairly flexible to use.

Cycle time: Due to the speed of the operations in producing parts from powder, economical quantities are high. Production volumes of at least 20,000 to 50,000 are necessary to obtain a cost advantage. Larger and complicated parts may prove economical at production volumes as low as 500-5000 pieces. Even though the cycle time for compaction of a part is small, the sintering is a relatively slow and time consuming process.

Operating costs: High costs of powders and normal die costs, which depends on the complexity of the part, preclude small production quantities. Labor costs are low and material utilization is excellent. Since this is a net-shape manufacturing process, secondary operations are minimal or absent, which also reduces the operating costs.

Quality: The dimensional accuracy of the parts produced by powder metallurgy is extremely high. Tolerances range from ±0.0002 inch (±0.006 mm) in small bores after repressing to ±0.005 inch (±0.13 mm) in larger dimensions on parts that are not repressed. Cross sectional dimensions can be held to closer tolerances than those of dimensions in the direction of pressing.

Shapes: Power-metal parts are normally small, less than 3 inches (75 mm) in the largest dimension. Complex shapes are feasible, but side walls are parallel and undercuts and screw threads must be provided by secondary operations. Thin sections, feathered edges, and narrow and deep splines must be avoided.

Products: Typical products made using powder metallurgy are cams, clutches, brake linings, self-lubricating bearings, slide blocks, levers, gears, bushings, ratchets, guides, spacers, splined parts, connecting rods, sprockets, pawls, and other mechanical parts for business machines, sewing machines, firearms and automobiles.

Materials: Various metals and ceramics are used in powder form to produce powder metal parts. Iron, carbon steel, allow steel, copper, brass, bronze, nickel, stainless steel, refractory metals (such as tungsten, molybdenum, and tantalum) and precious metals are the various metals used. Sometimes, a combination of two metals can also be used to combine the advantages of the individual metals. Cemented carbides such as tungsten carbide, molybdenum carbide, and tantalum carbide are made with a small amount of cobalt.

Advantages: Rapid production of parts with high dimensional accuracy, smooth surfaces, and excellent bearing properties. Parts can be somewhat intricate in shape. Scrap loss is low, since this is a near-net-shape manufacturing process. Special properties such as self-lubrication in porous bearings are an important advantage of powder metallurgy. Powder metallurgy components have good damping characteristics that result in quieter operation of mating parts. Metallic brake linings and clutch plates that include a nonmetallic abrasive powder are manufactured using this process.

Disadvantages: Size of parts is limited, and not all shapes can be produced. Powder and tooling costs limit the process to high-production applications. Undercuts are not feasible. There are also strength limitations.

Design rules: See Appendix D.10

APPENDIX B

STILLS OF THE MANUFACTURING PROCESSES

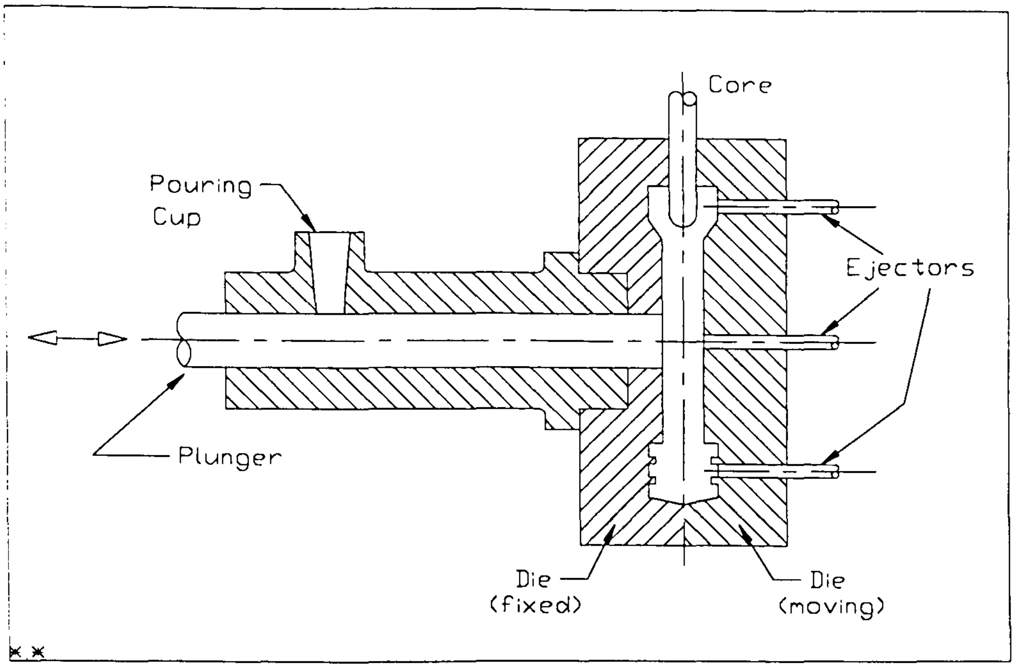


Fig. B.1 should be pressure die casting but I cannot find the file!

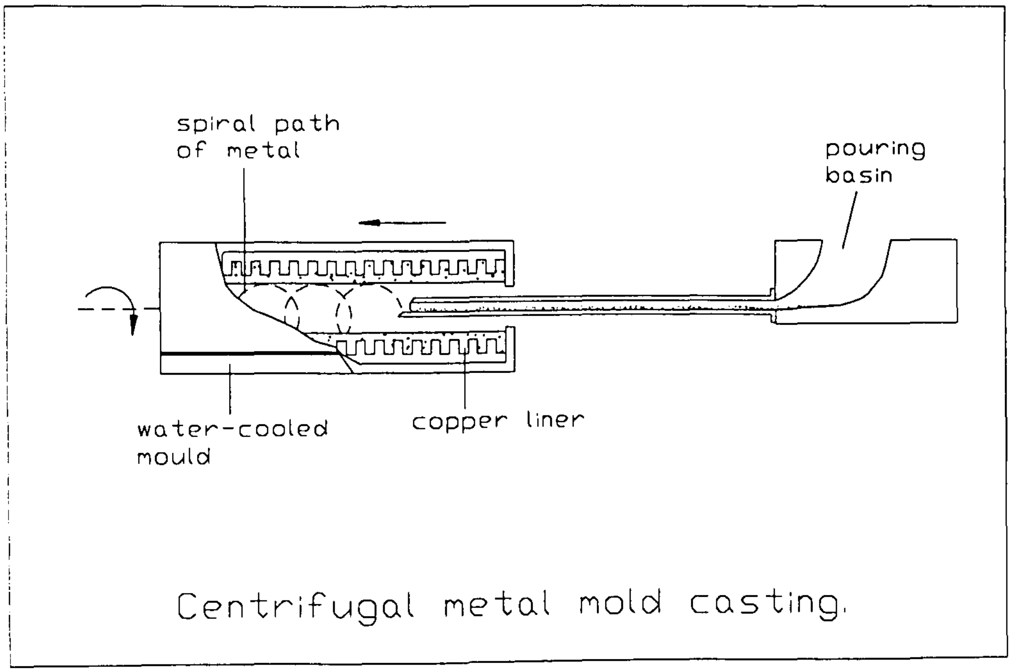


Fig. B.2 Centrifugal casting

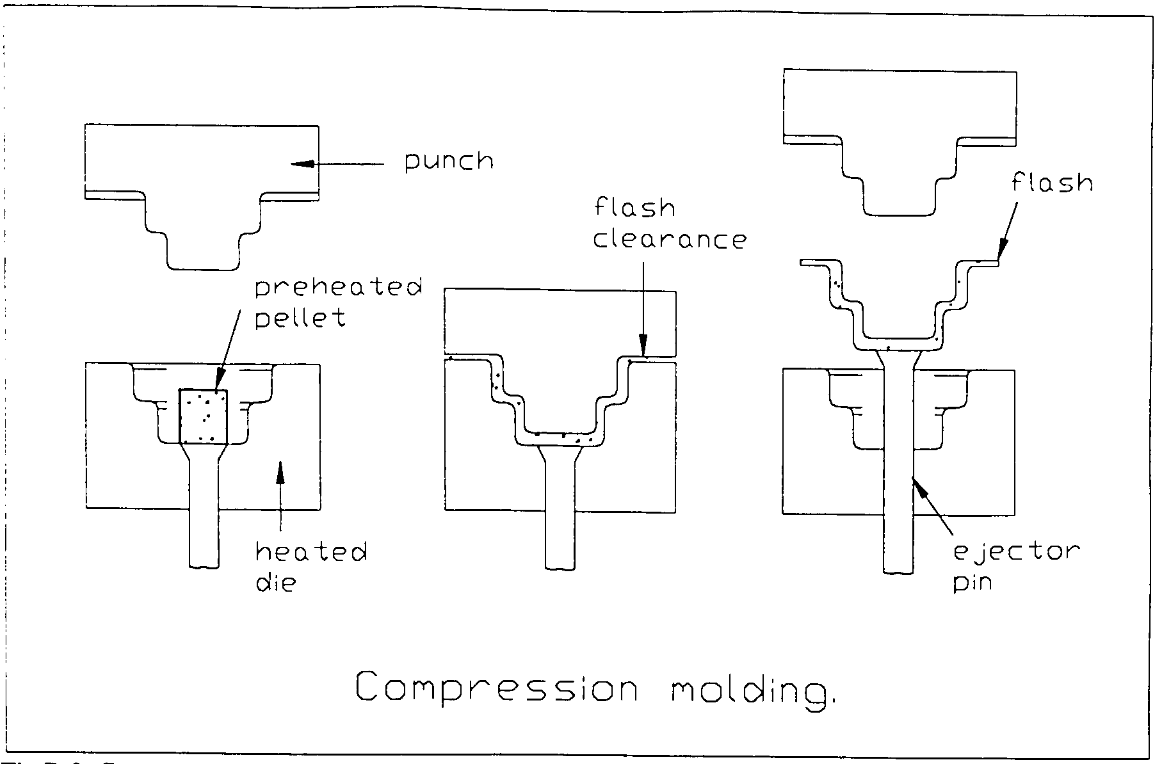


Fig B.3 Compression molding

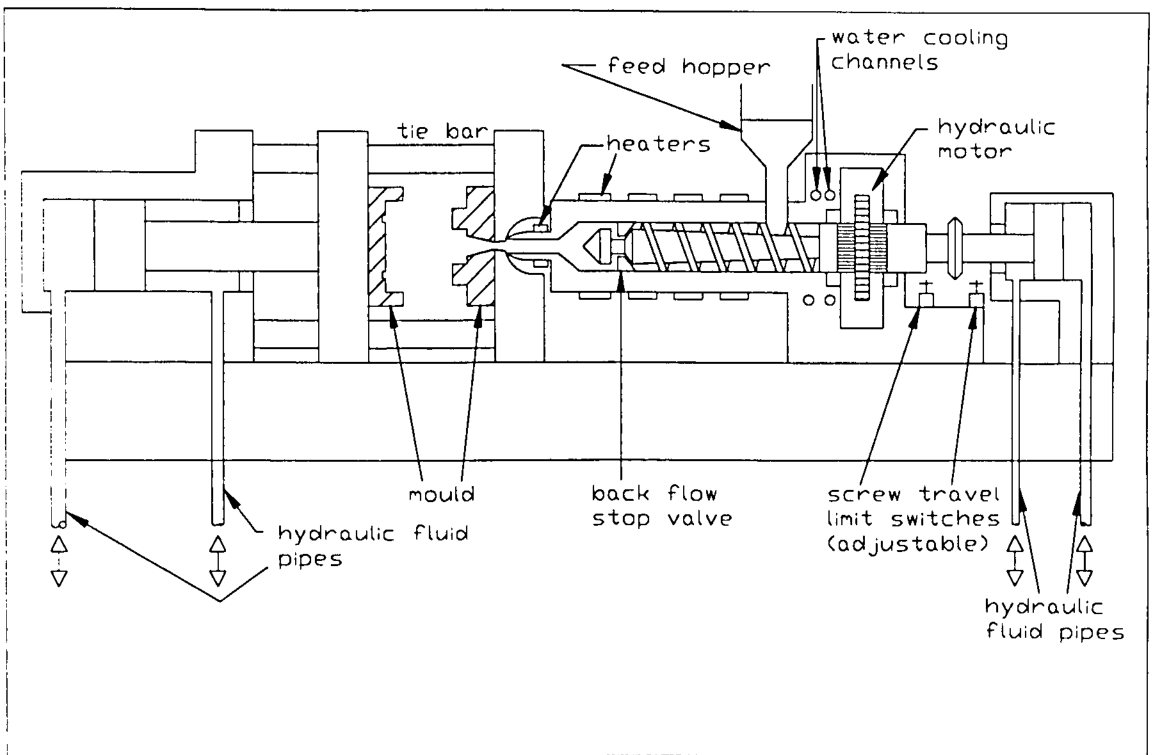


Fig. B.4 A typical injection molding machine.

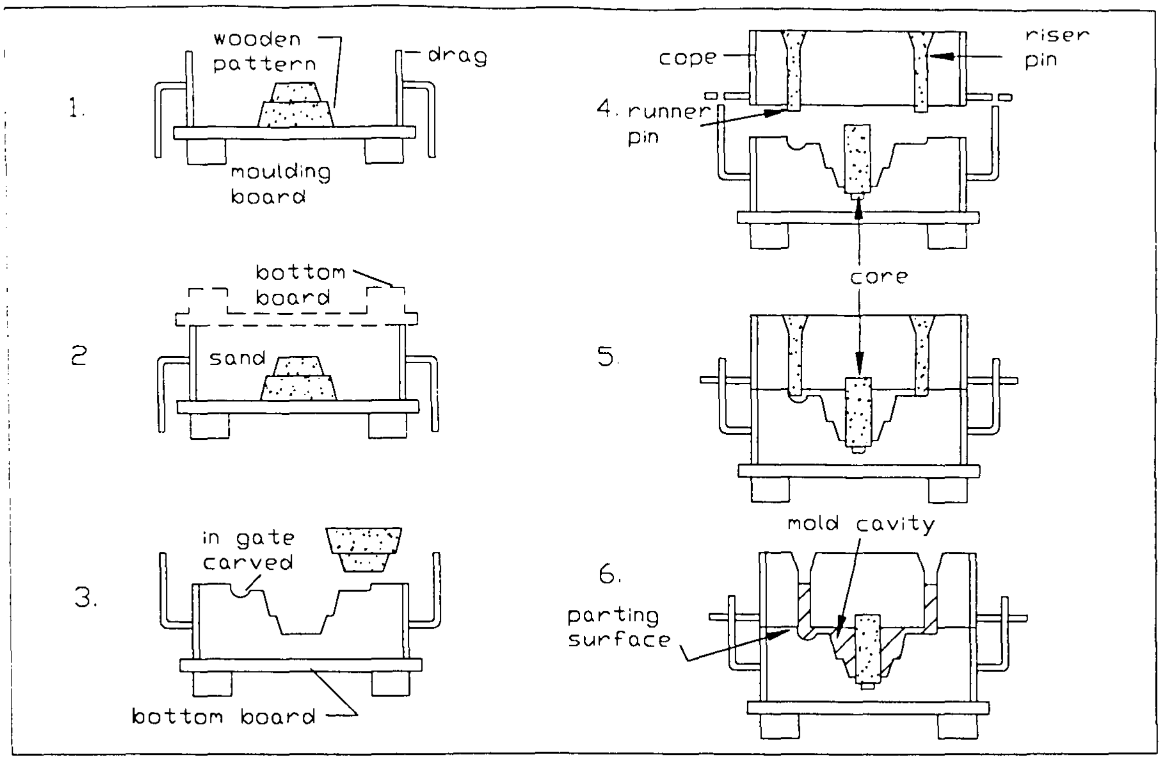


Fig. B.5 Sand casting

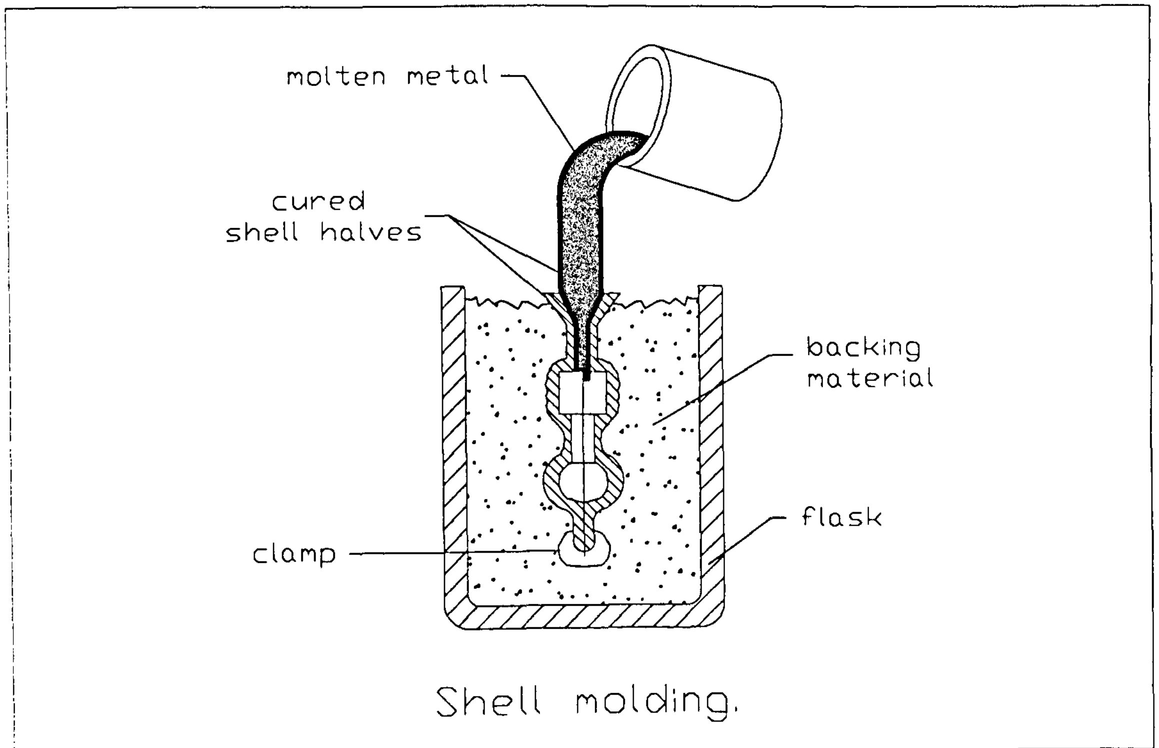


Fig. B.6 Shell mold casting

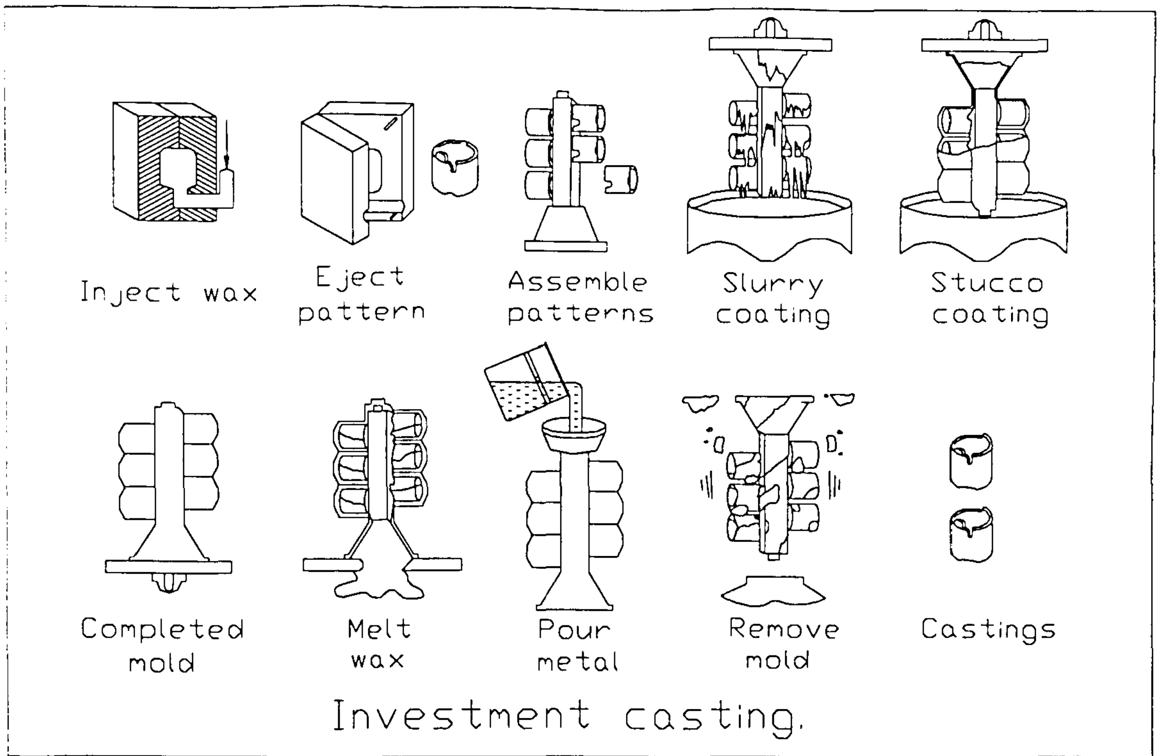


Fig. B.7 Investment casting

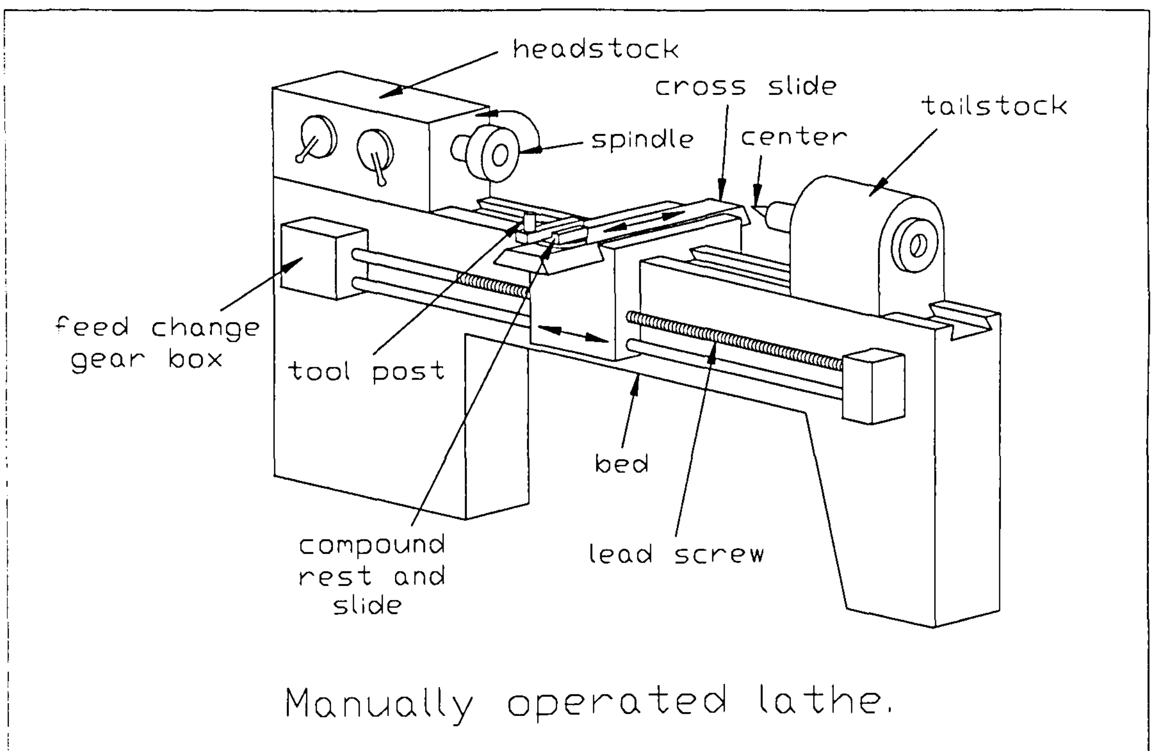


Fig. B.8 Turning

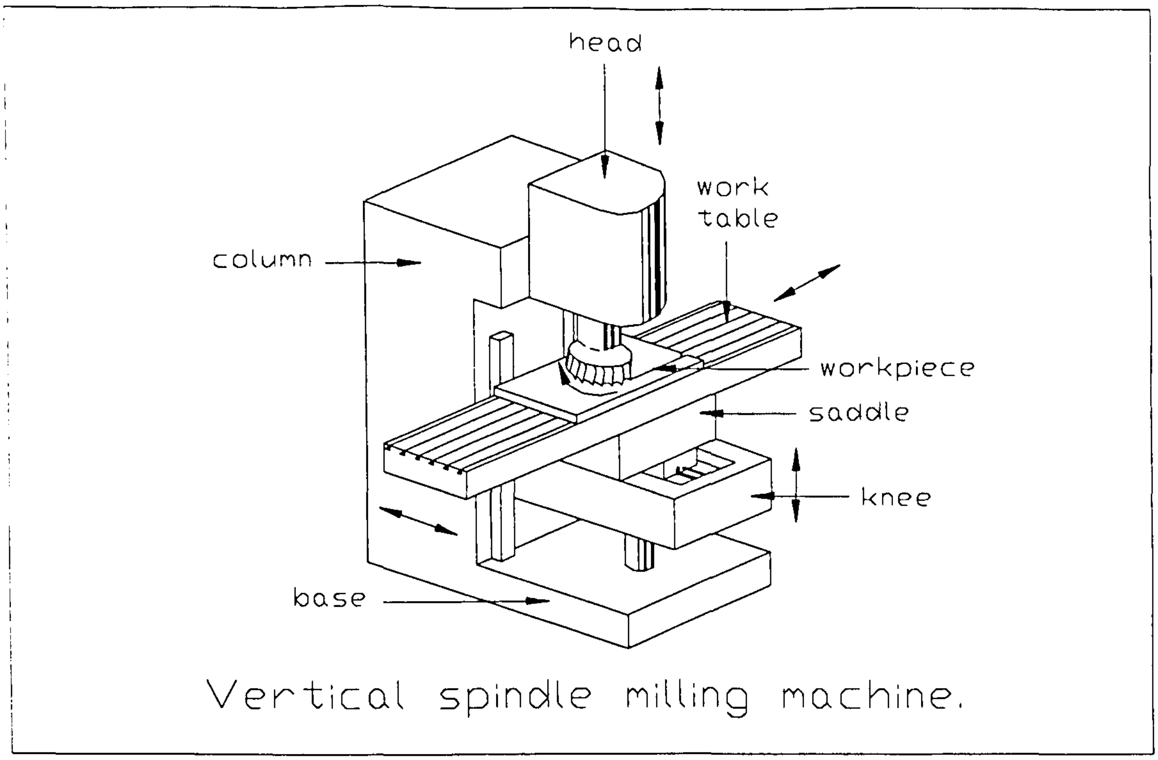


Fig. B.9 Milling(multiple point cutting)

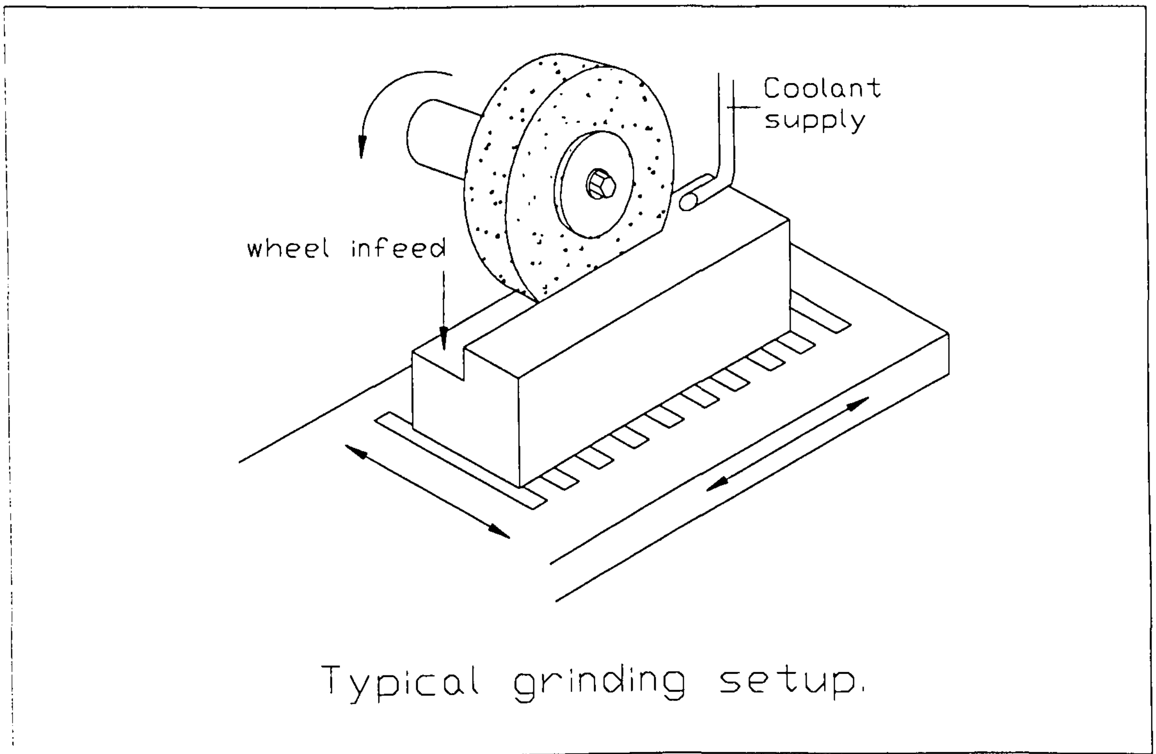


Fig. B.10 Grinding

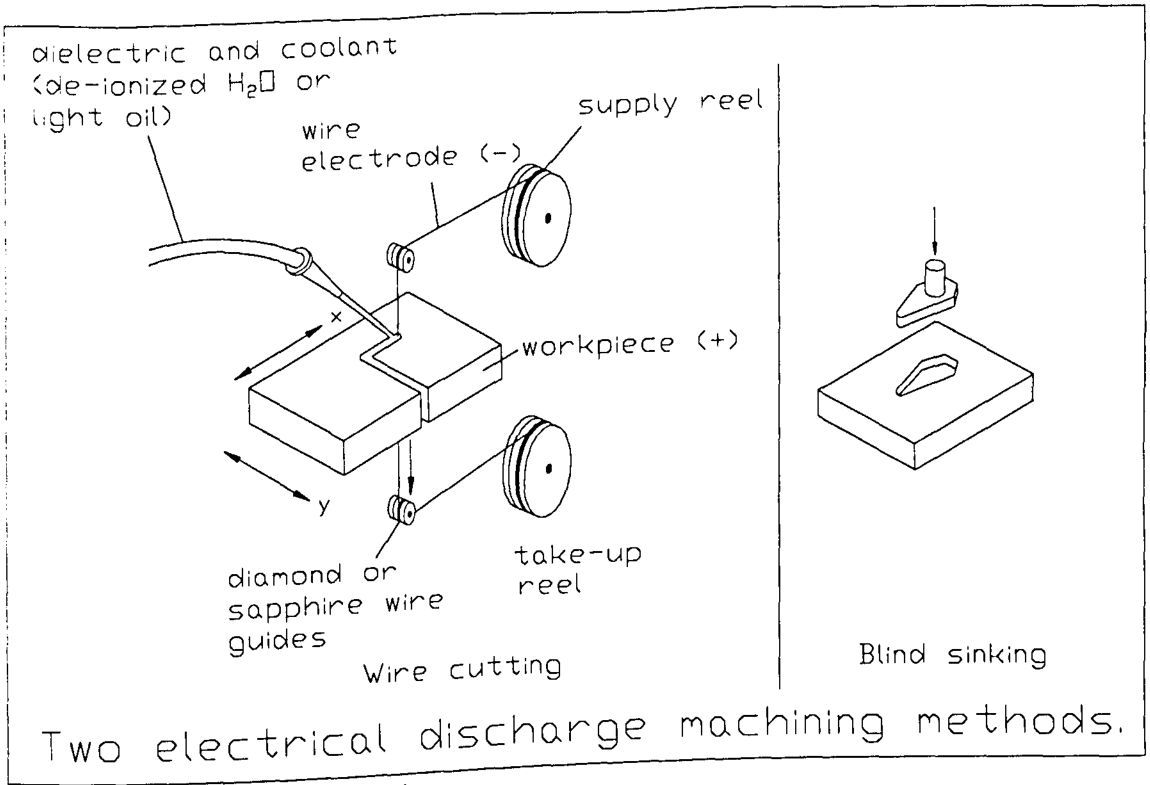


Fig. B.11 Electric discharge machining

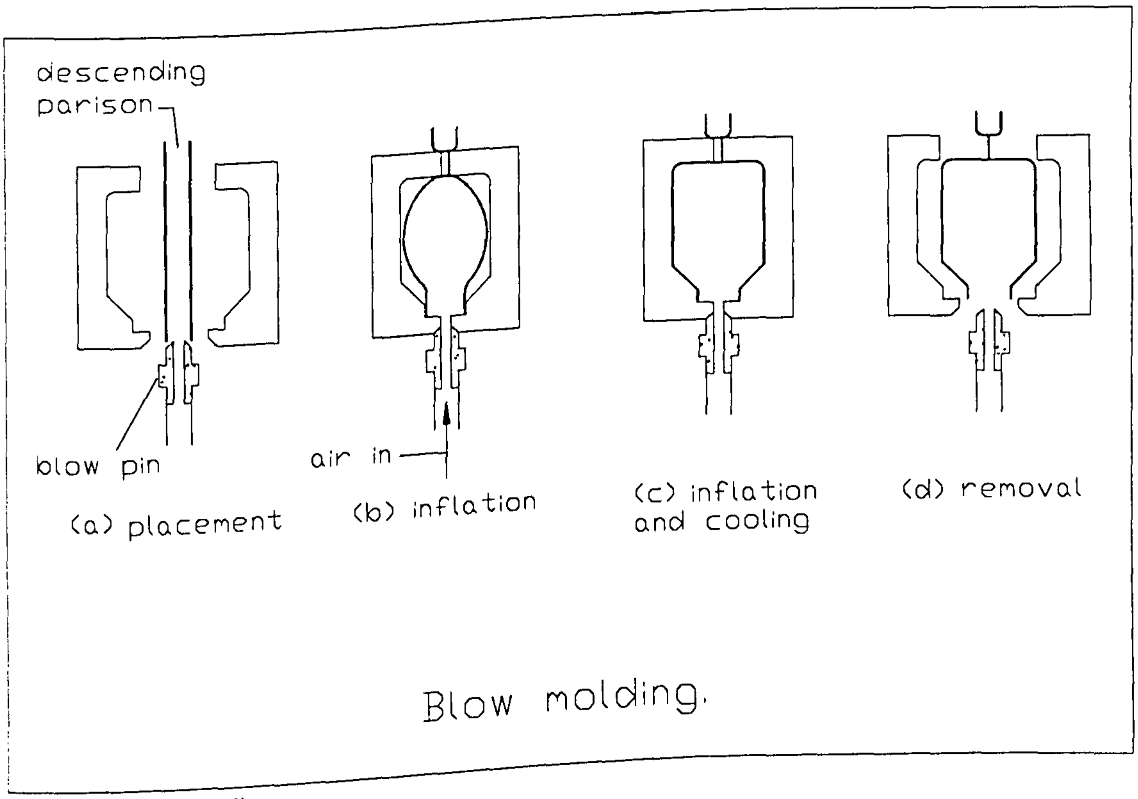


Fig. B.12 Blow molding

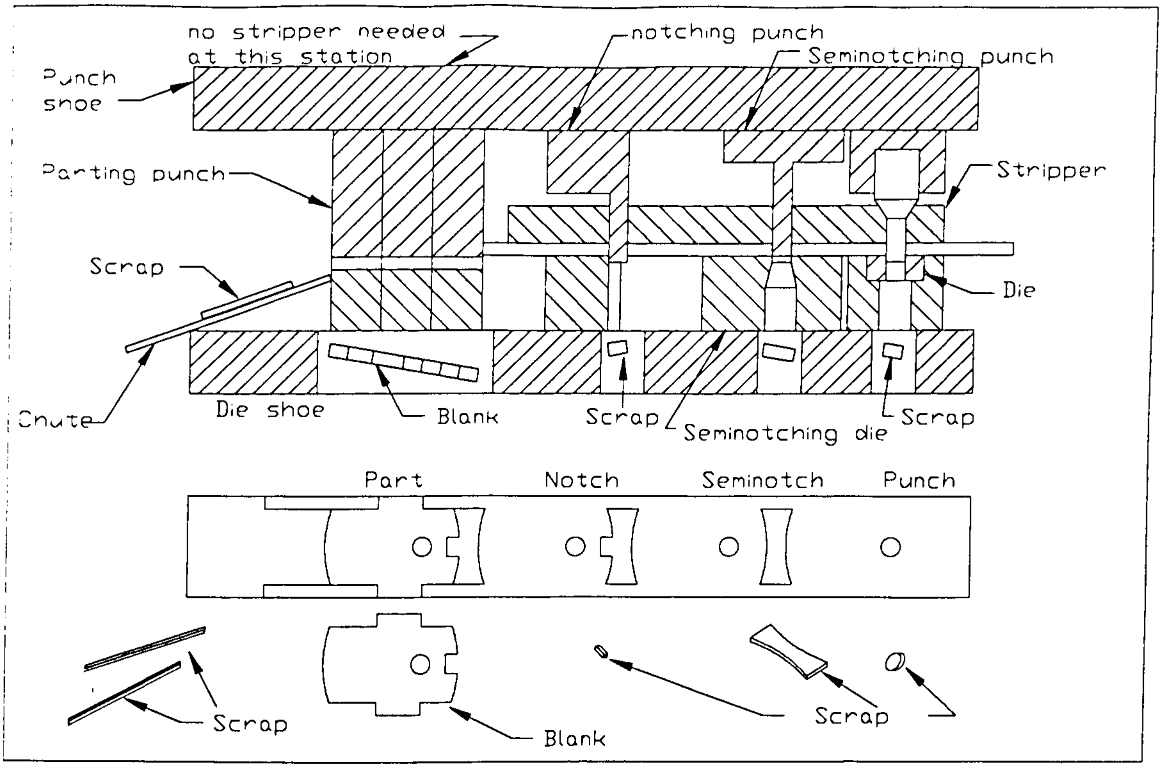


Fig. B.13 Sheet metal working

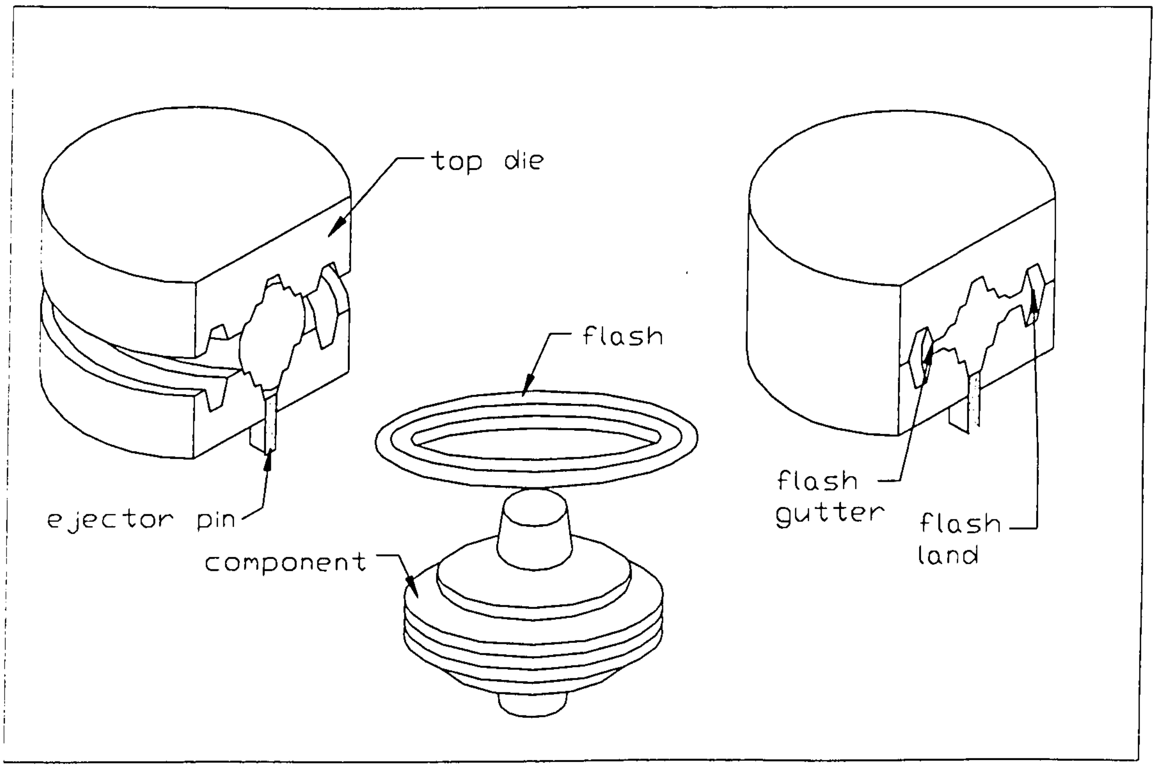


Fig. B.14 Forging

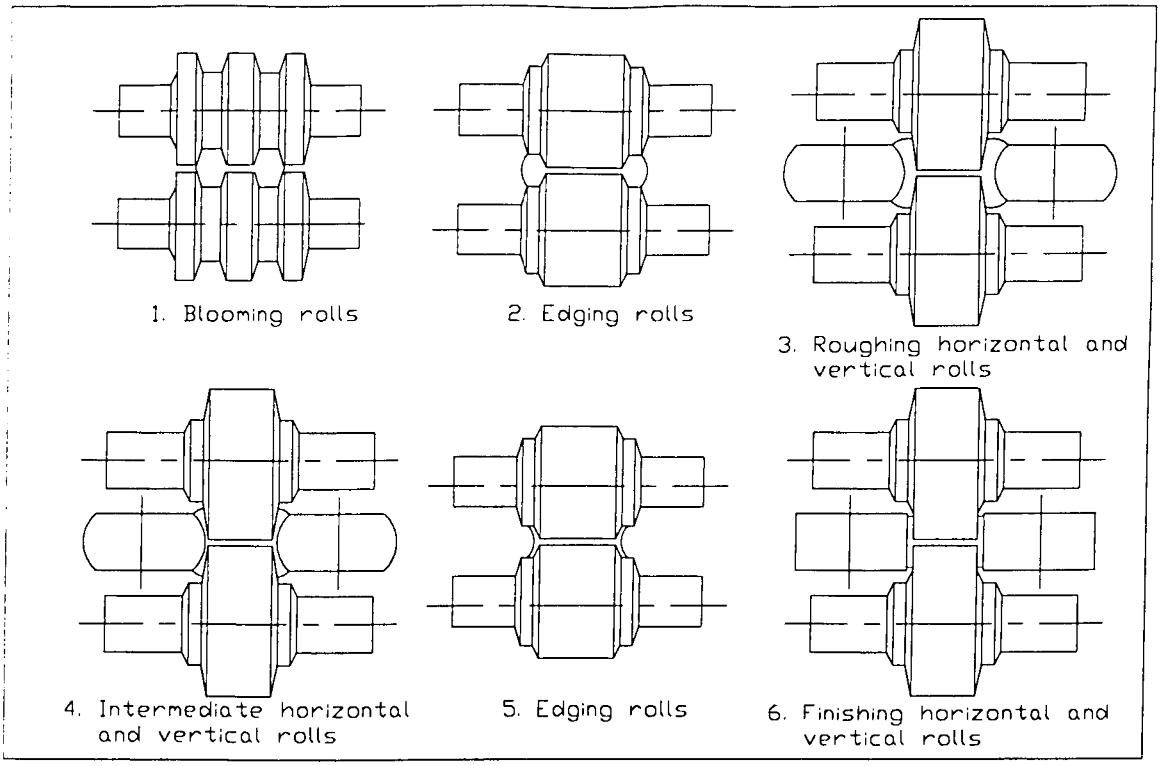


Fig. B.15 Rolling

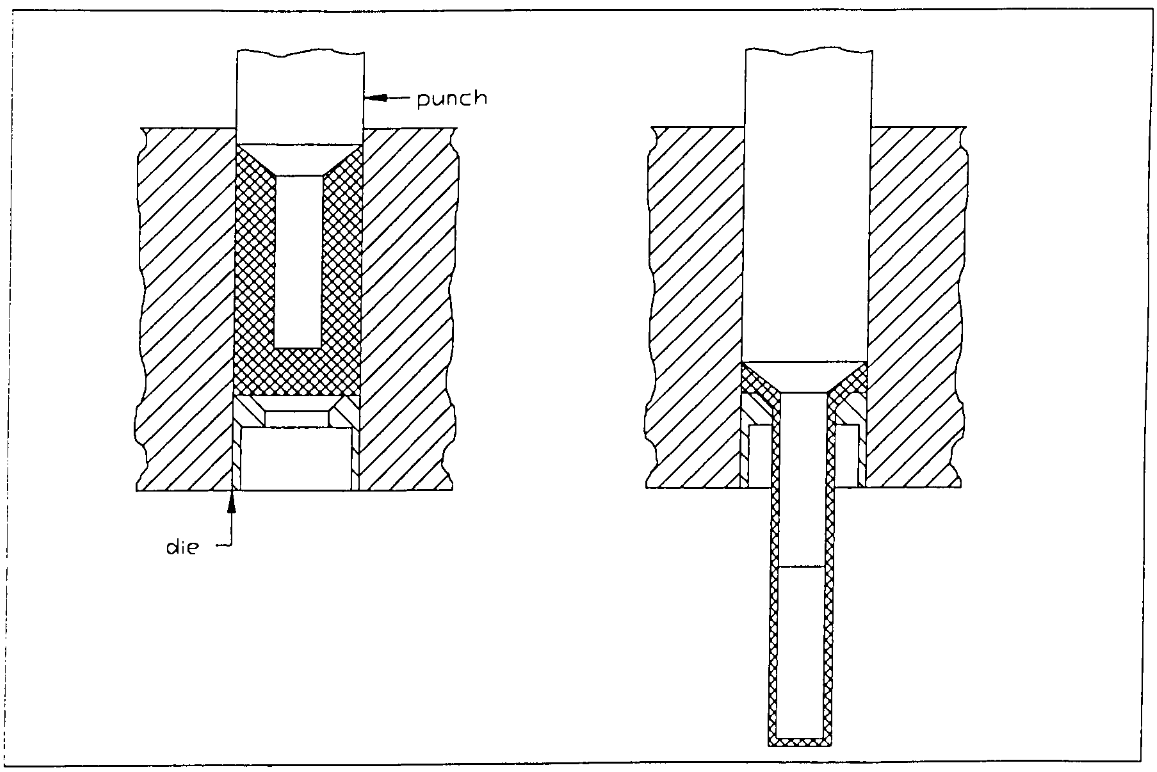


Fig. B.16 Forward extrusion

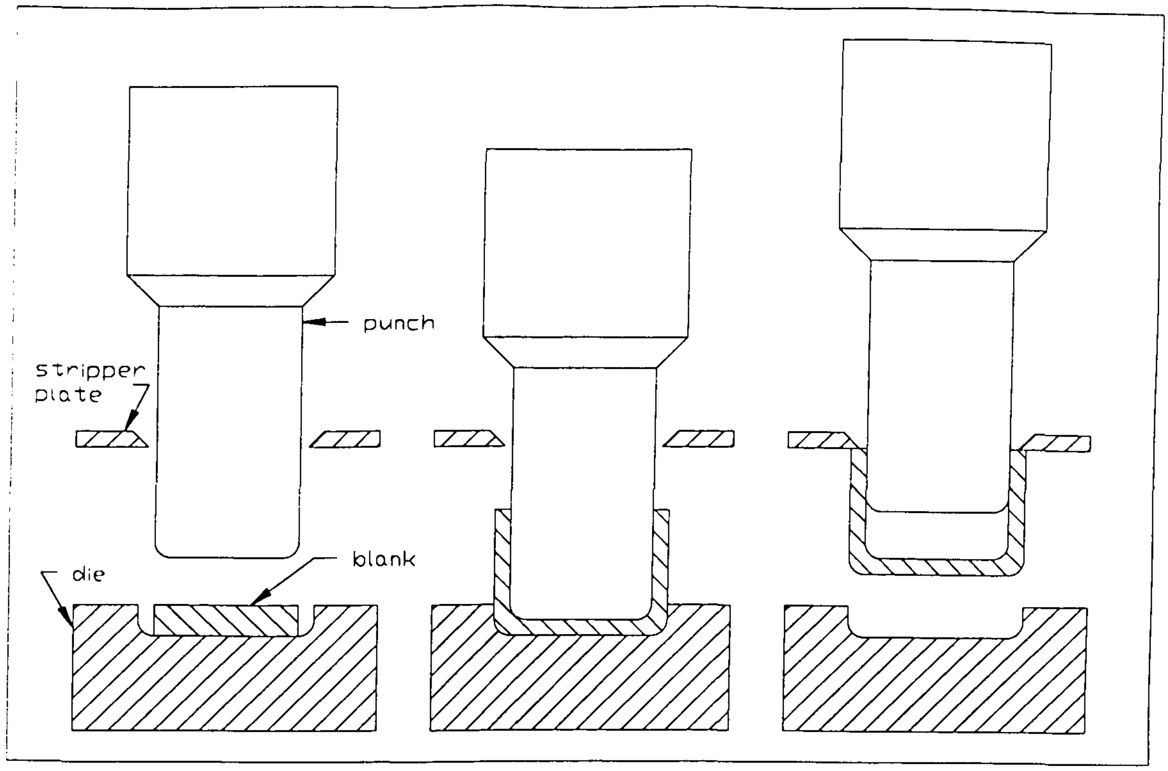


Fig. B.17 Backward extrusion

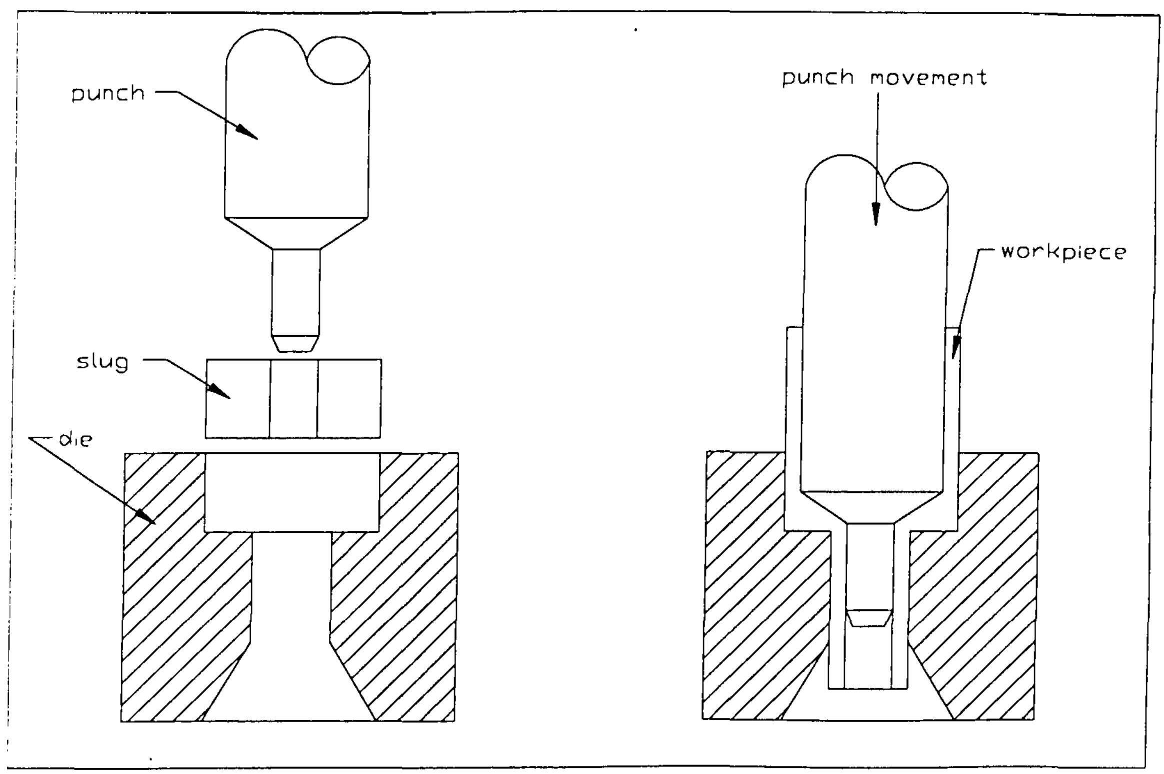


Fig. B.18 Forward and backward impact extrusion

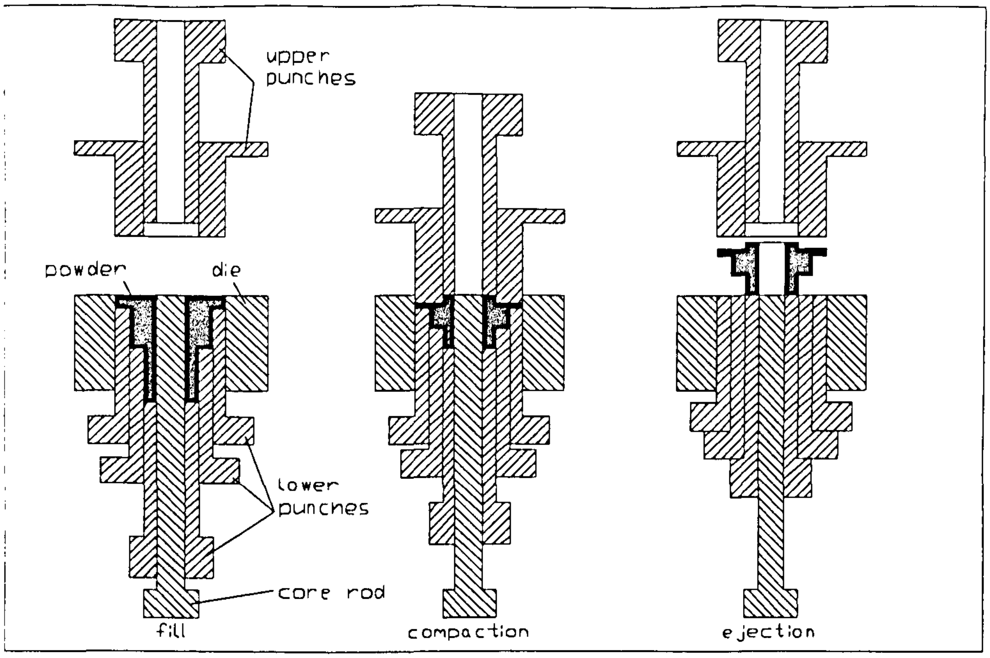
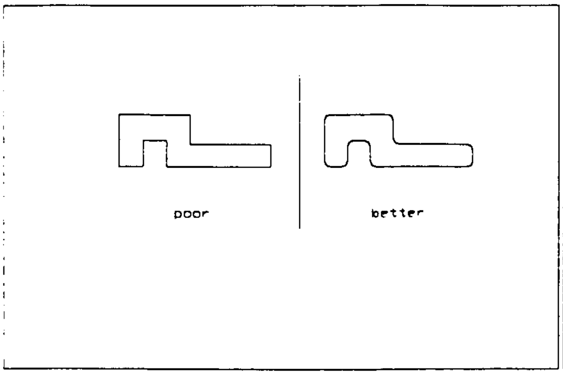


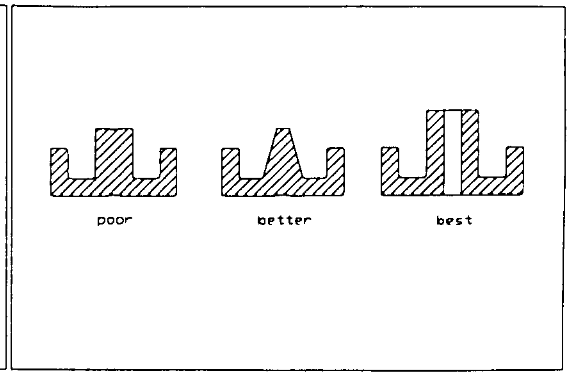
Fig. B.19 Powder metallurgy

APPENDIX C

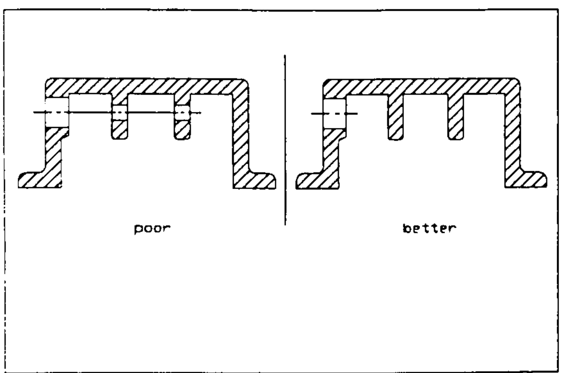
C.1 - Design Guidelines for Casting



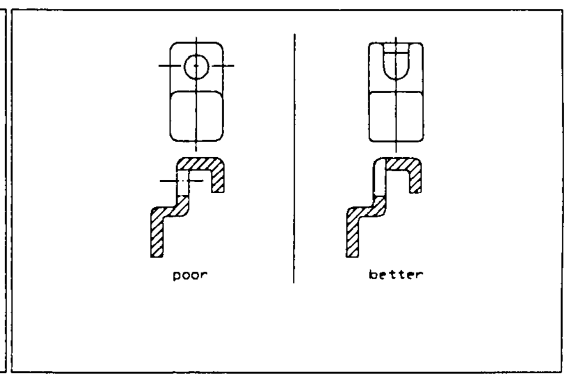
DG-C-1: Avoid sharp corners with generous fillets and radii.



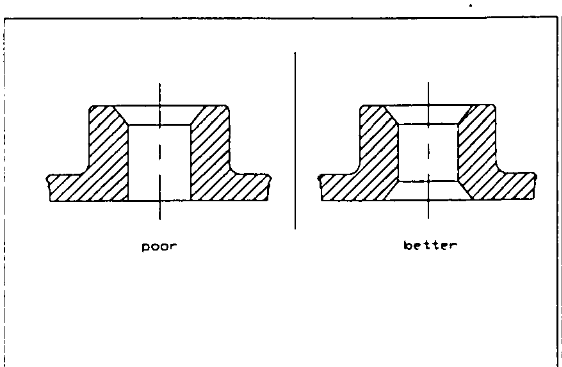
DG-C-2: Keep walls uniform and thin.



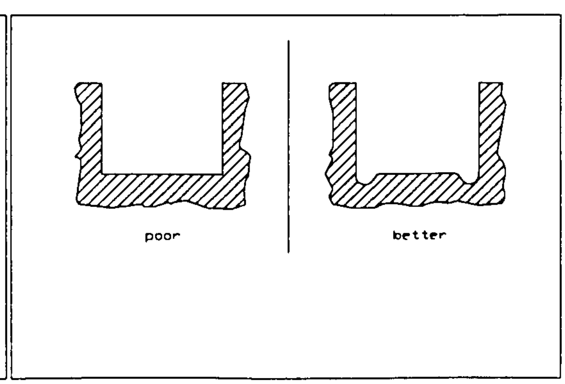
DG-C-3: Avoid core slides that must fit accurately through both die halves. Drill holes in internal ribs.



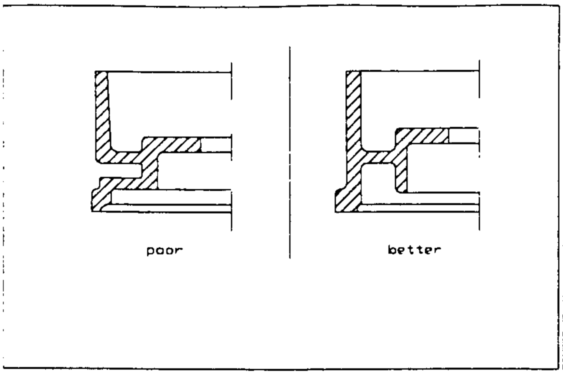
DG-C-4: Core slides should be avoided



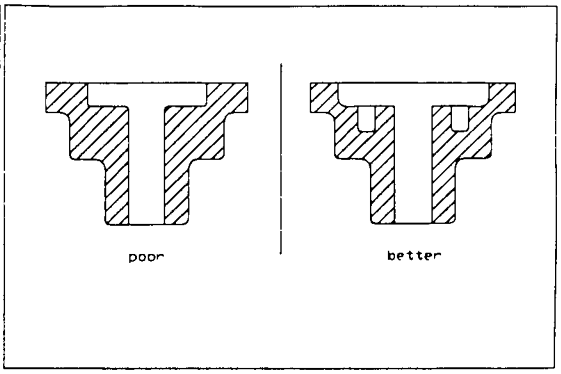
DG-C-5: Countersink on both sides any through holes that are to be tapped.



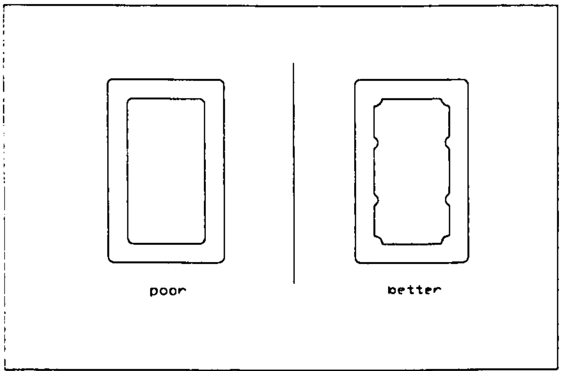
DG-C-6: Avoid sharp corners in cavities.



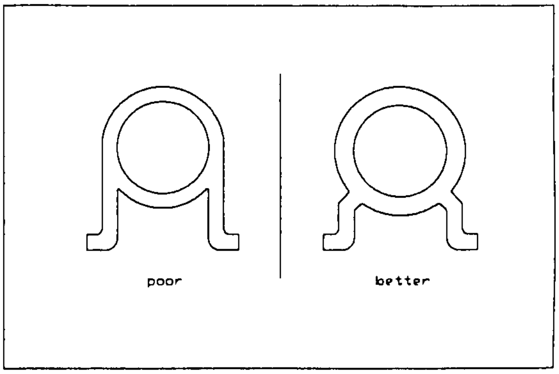
DG-C-7: Avoid external-wall undercuts.



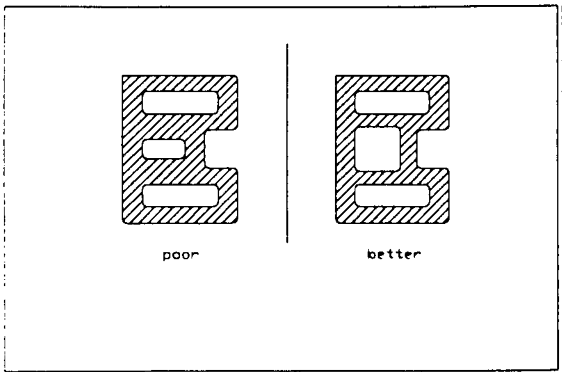
DG-C-8: When adjacent to a cored area, introduce further coring to remove mass and obtain uniform wall thickness.



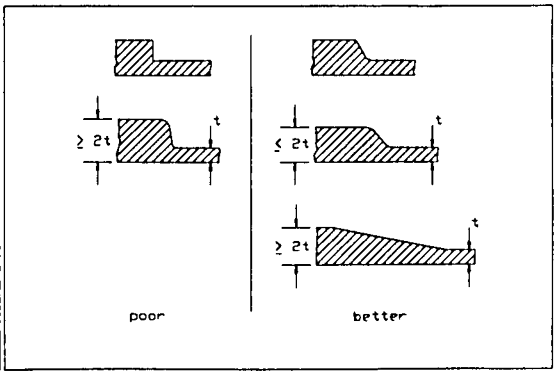
DG-C-9: Strengthen box-shaped components by incorporating internal ribs that run the full depth of part.



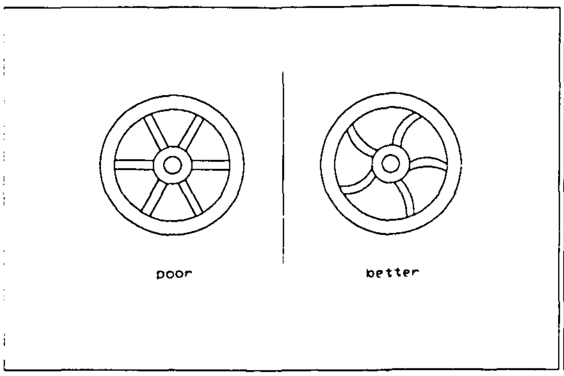
DG-C-10: The intersection of two walls should be at right angles.



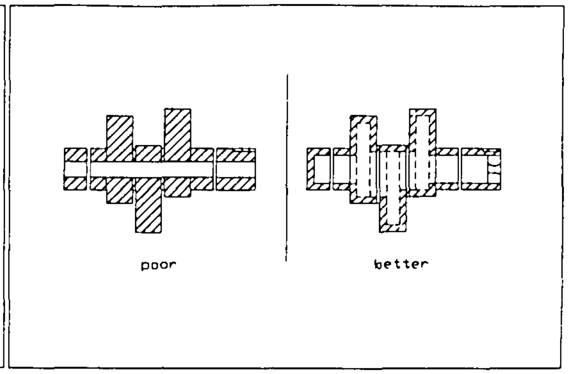
DG-C-11: Interior walls should be 20% thinner than exterior walls.



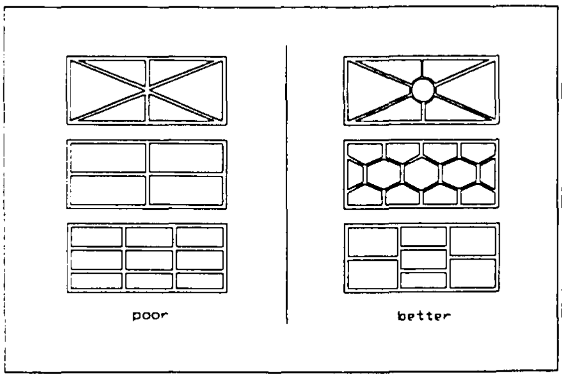
DG-C-12: Design rules for areas where section thickness must change.



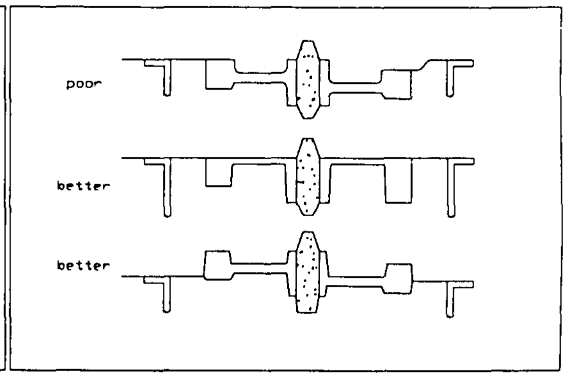
DG-C-13: Use an odd number of curved wheel spokes.



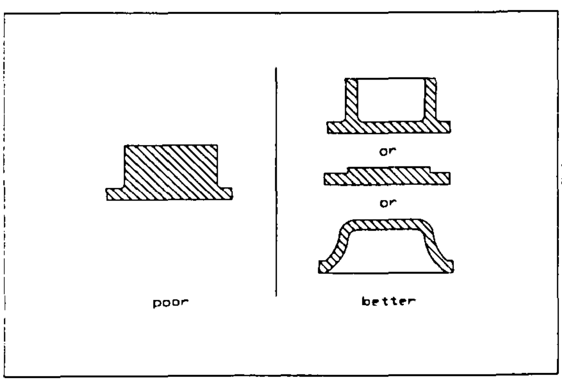
DG-C-14: Keep wall thickness uniform.



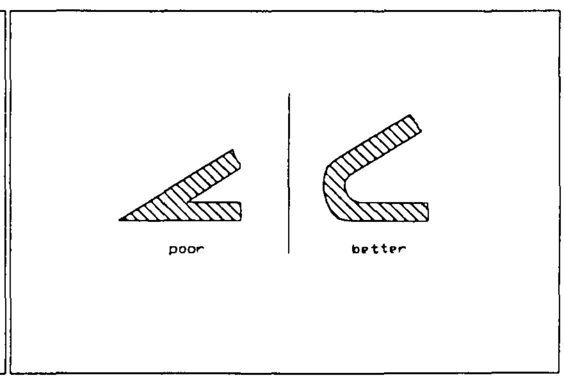
DG-C-15: Reduce number of ribs intersecting at a common point.



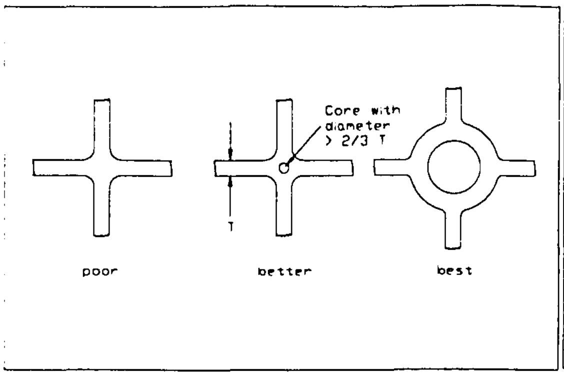
DG-C-16: Straight parting lines are more economical than stepped parting lines.



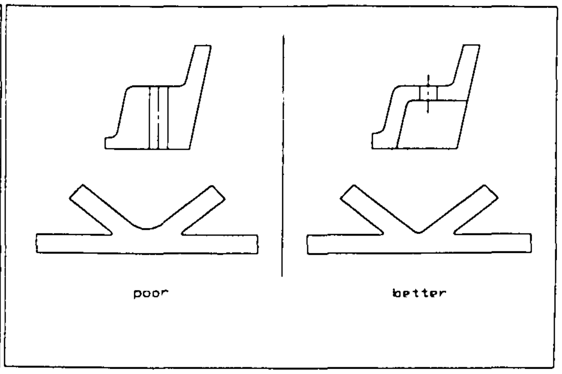
DG-C-17: Suggestions for minimizing material thickness at bosses.



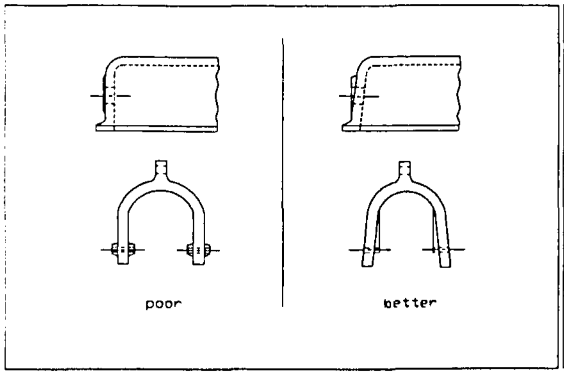
DG-C-18: Avoid acute angles.



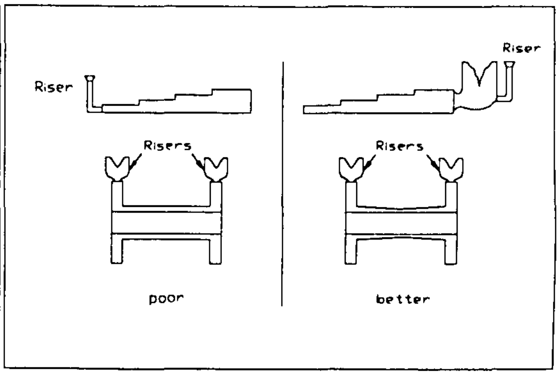
DG-C-19: Design alternatives to prevent voids at rib and wall intersections.



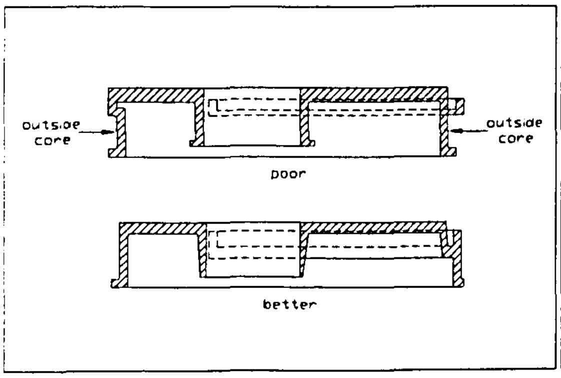
DG-C-20: Maintain uniformity of cross-sections.



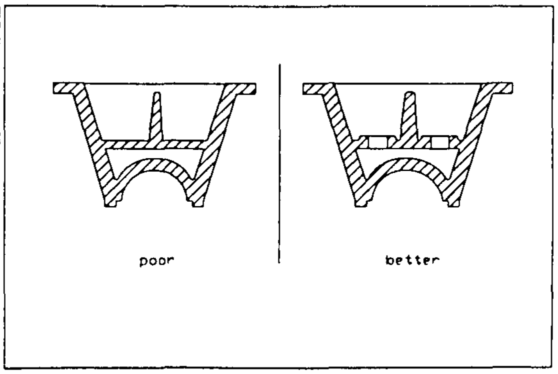
DG-C-21: Eliminate undercuts to minimize use of cores.



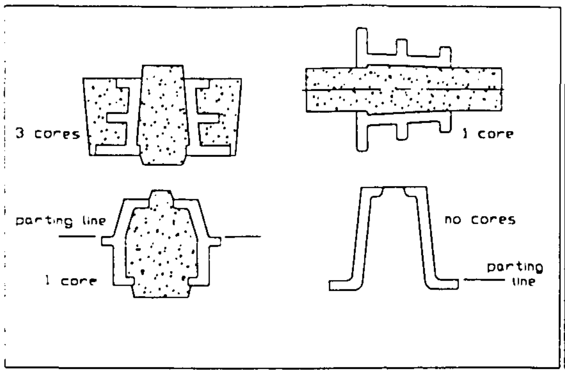
DG-C-22: Locate risers to facilitate void-free filling of molds.



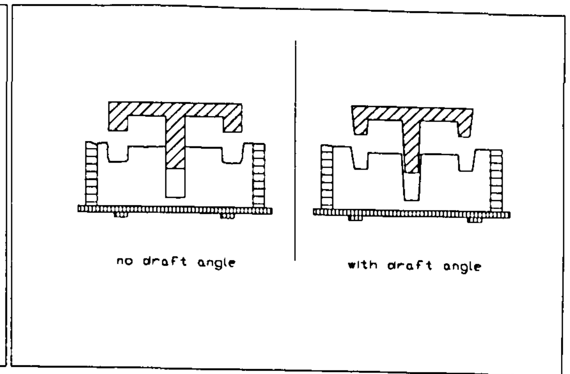
DG-C-23: Eliminate external undercuts to remove need for outside cores.



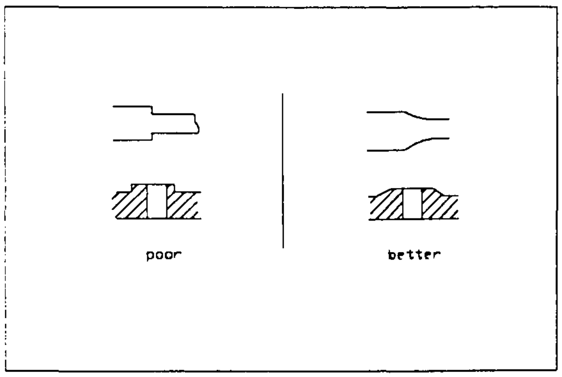
DG-C-24: Vent holes are required to permit gases to escape during pouring.



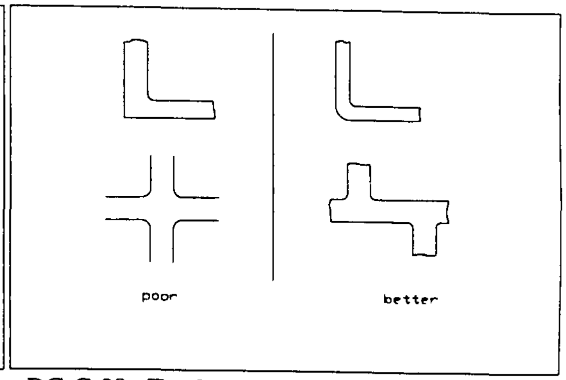
DG-C-25: Minimize use of cores by eliminating undercuts.



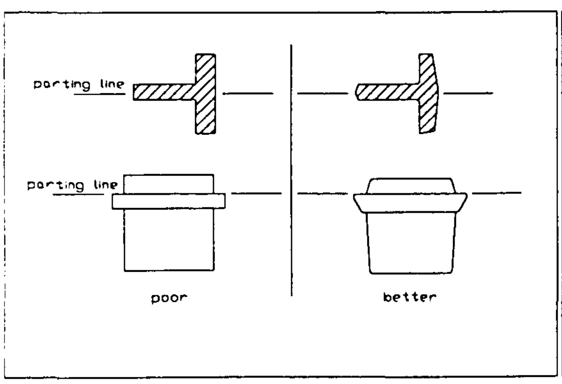
DG-C-26: Provide draft angle for easy removal of mold.



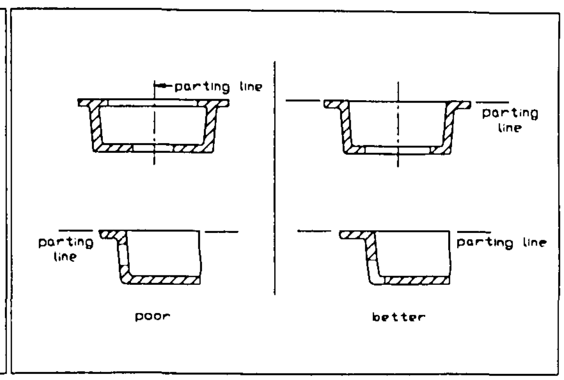
DG-C-27: Avoid sharp corners.



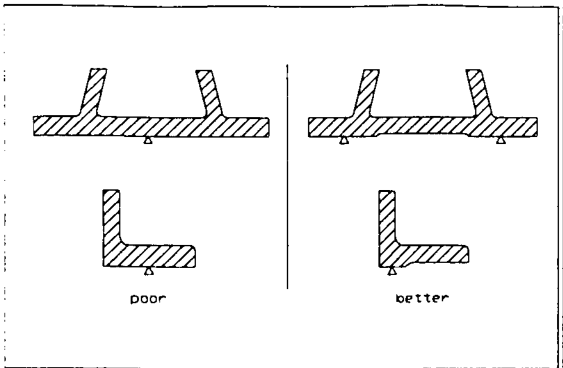
DG-C-28: Try for uniform cross-sections.



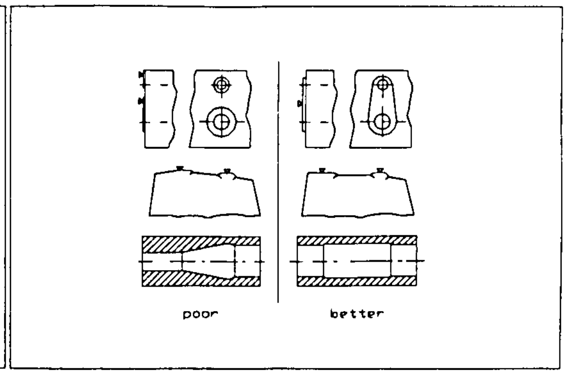
DG-C-29: Provide tapers from the parting line



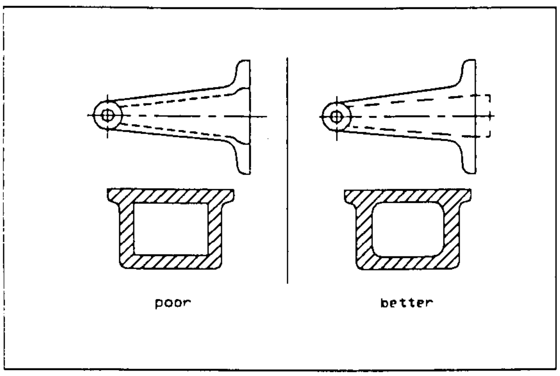
DG-C-30: Aim at undivided patterns by using open cross sections.



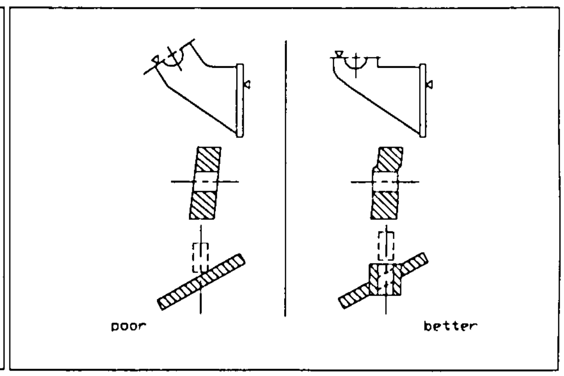
DG-C-31: Avoid unnecessary machining by breaking up large surfaces.



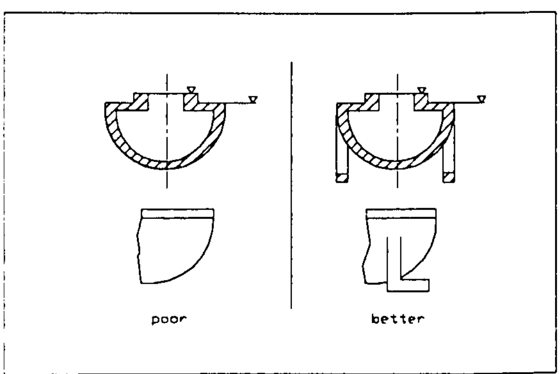
DG-C-32: Combine machining processes by the appropriate arrangement of machining and boring surfaces.



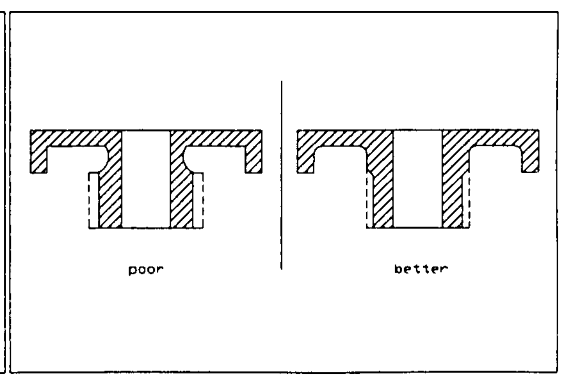
DG-C-33: Choose simple shapes for patterns and cores.



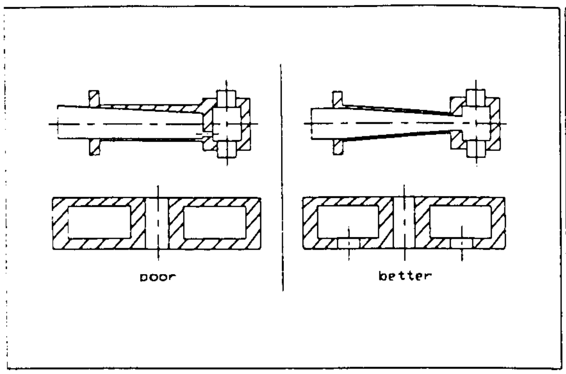
DG-C-34: Avoid machining and boring of sloping surfaces.



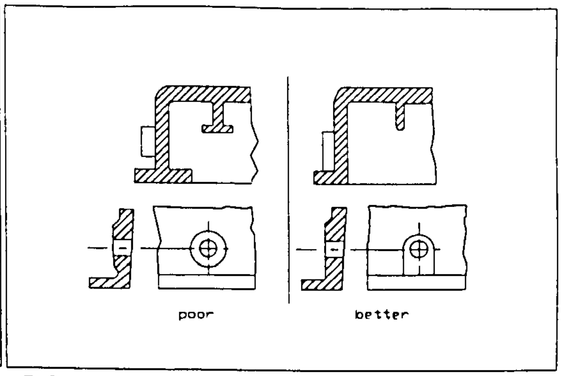
DG-C-35: Provide adequate support surfaces.



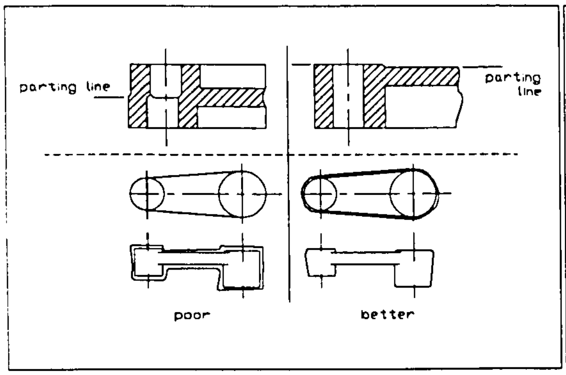
DG-C-36: Arrange castings to ease machining.



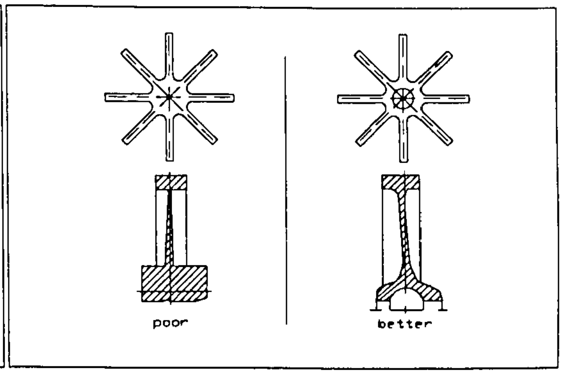
DG-C-37: Ensure accurate location of cores



DG-C-38: Arrange ribs so that pattern can be removed; avoid undercuts.

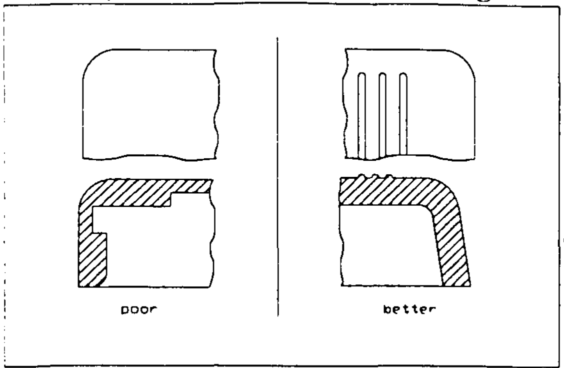


DG-C-39: Set parting lines to avoid misalignment and to permit easy removal of the flash.

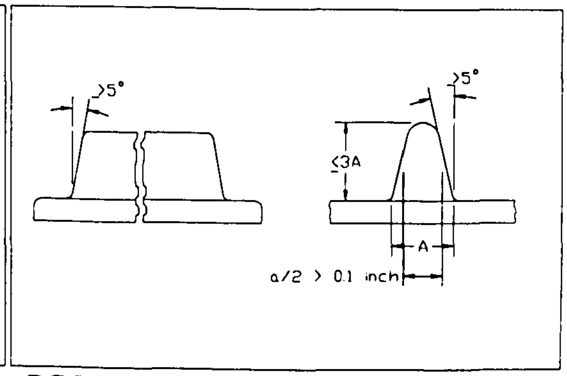


DG-C-40: Aim at uniform wall thicknesses and cross-sections and at gradual changes.

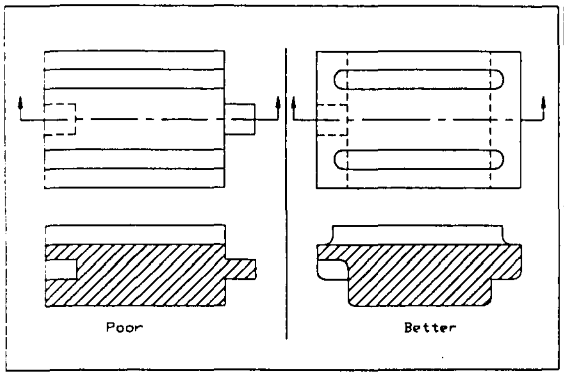
C.2 - Design Guidelines for Injection Molding and Compression Molding



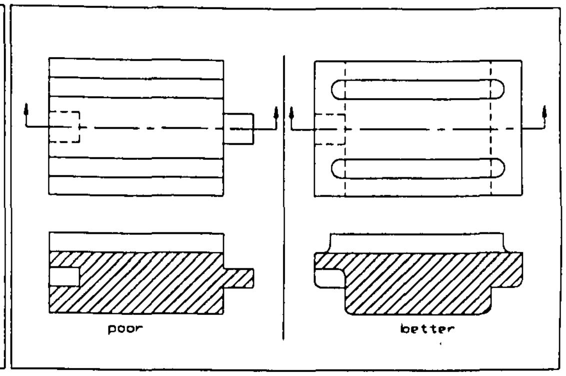
DG-IMCM-1: Avoid undercuts and variation in wall thickness. Use decorative designs to conceal shrinkage.



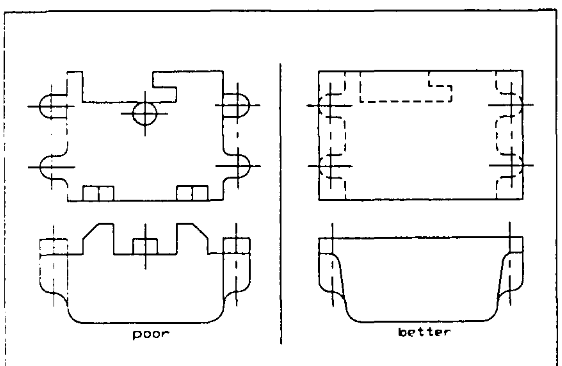
DG-IMCM-2: Guidelines for rib proportions.



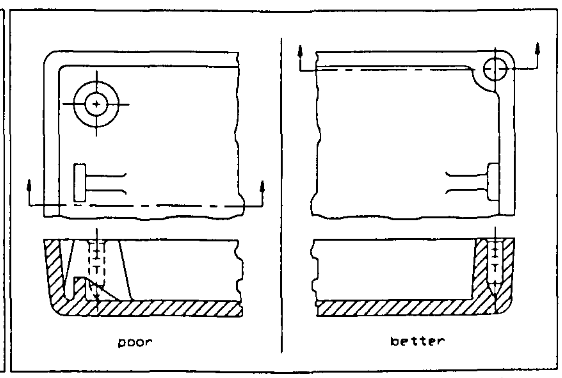
DG-IMCM-3: Avoid holes and side projections.



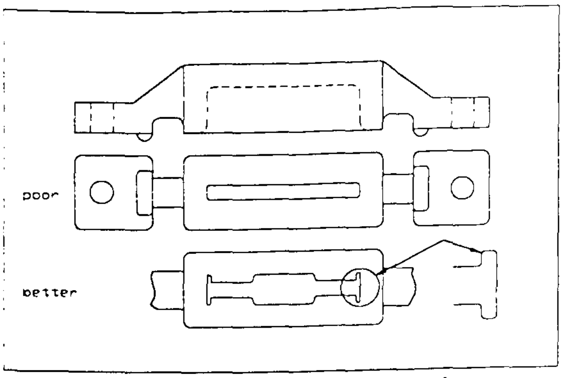
DG-IMCM-4: Avoid holes and side projections.



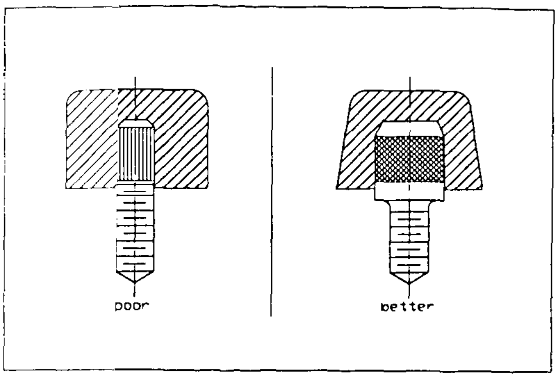
DG-IMCM-5: Avoid intricate and delicate sections



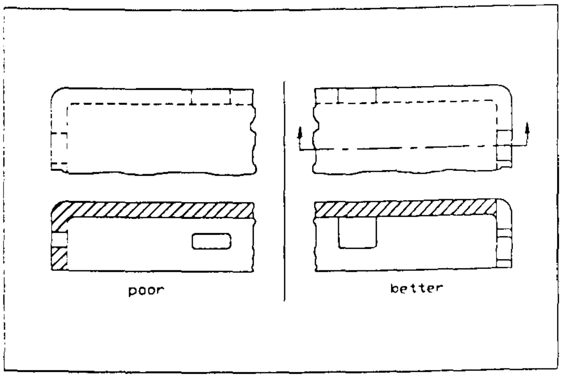
DG-IMCM-6: Design for sturdy mold members.



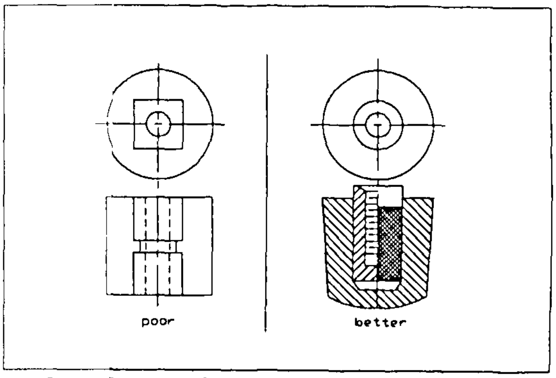
DG-IMCM-7: Avoid deep and narrow slots.



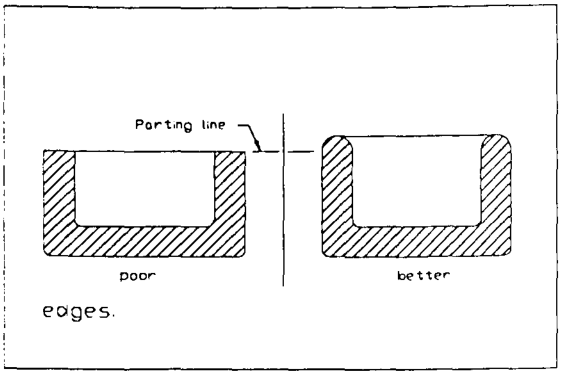
DG-IMCM-8: Keep threaded portion of the insert out of the molding.



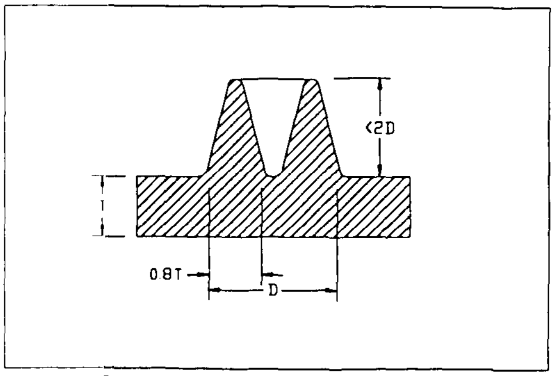
DG-IMCM-9: Design for side openings that can be made by mold's vertical members.



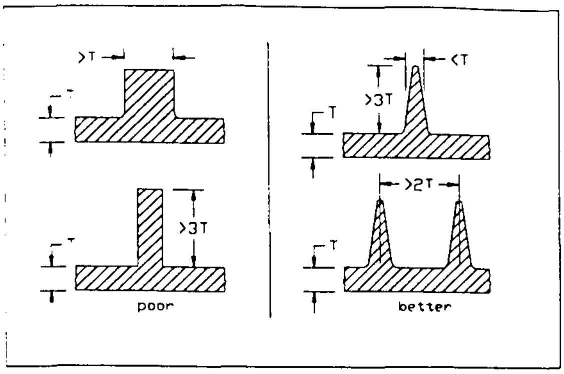
DG-IMCM-10: Guidelines for inserts.



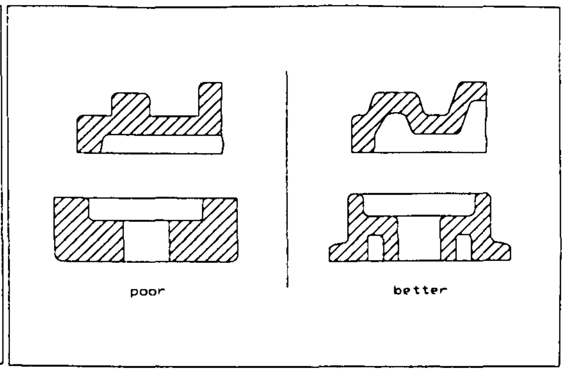
DG-IMCM-11: For brittle material, avoid sharp edges.



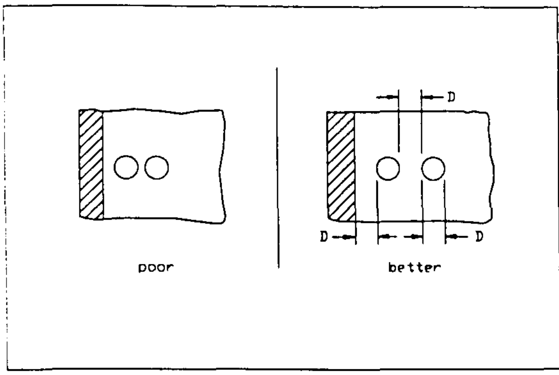
DG-IMCM-12: Guidelines for bosses in thermoset parts.



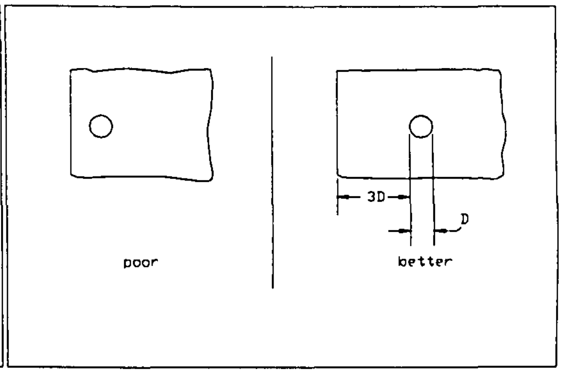
DG-IMCM-13: Guidelines for ribs in thermoset parts.



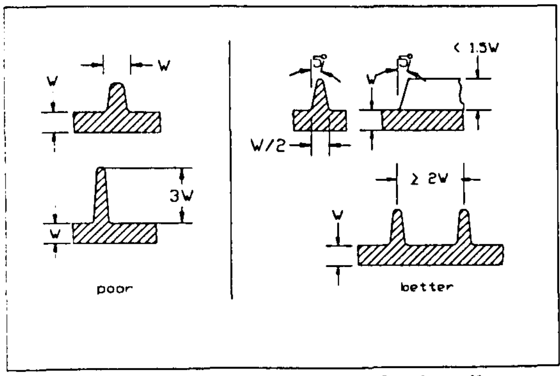
DG-IMCM-14: Maintain uniform wall thickness and provide for gradual changes in wall thickness.



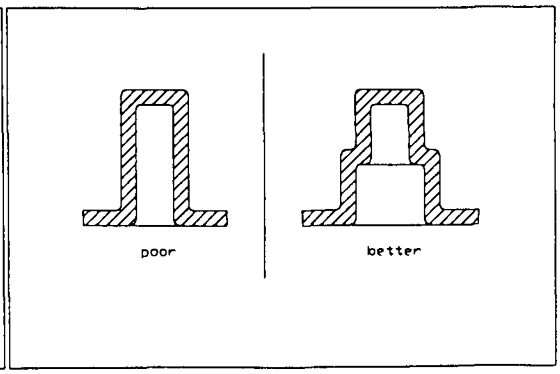
DG-IMCM-15:. Minimum spacing for holes and sidewalls.



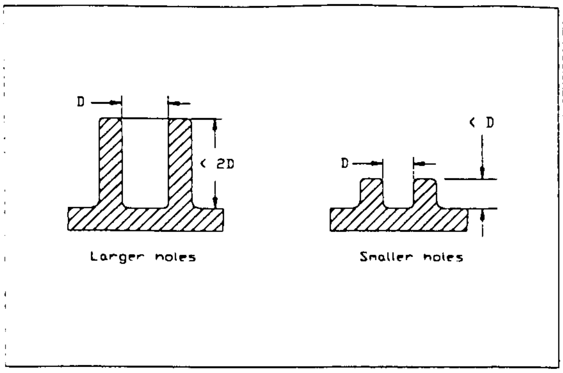
DG-IMCM-16:. Minimum distance between a hole and the edge of the part.



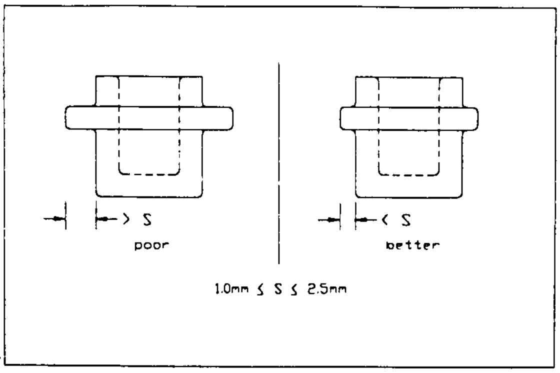
DG-IMCM-17:Guidelines for reinforcing ribs.



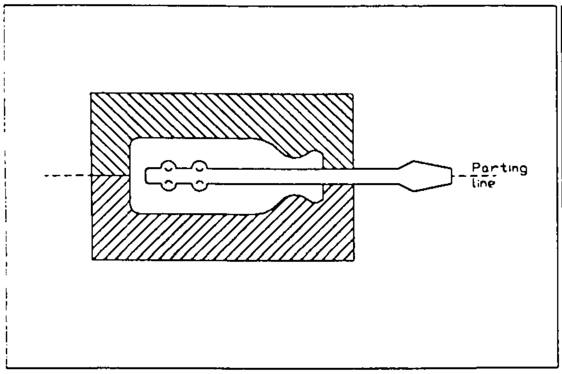
DG-IMCM-18: For a deep blind hole, use a stepped diameter.



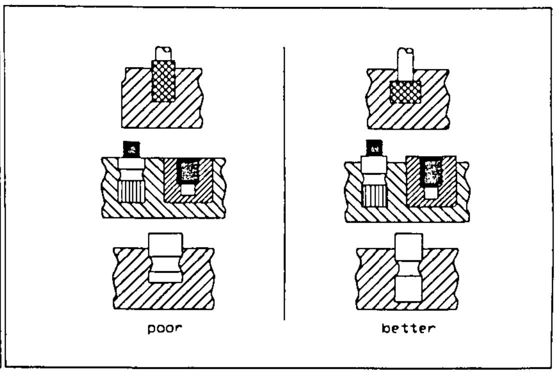
DG-IMCM-19: Recommended depth limits for blind holes.



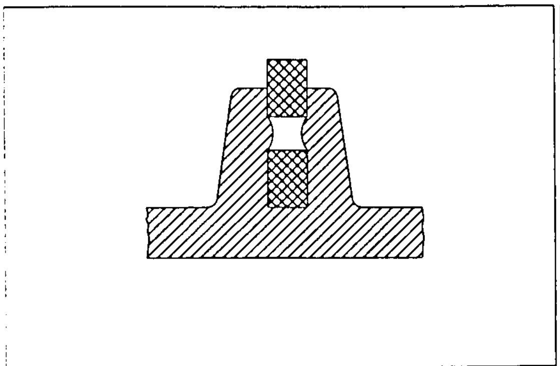
DG-IMCM-20:. Allowable undercut, which varies as a function of the material.



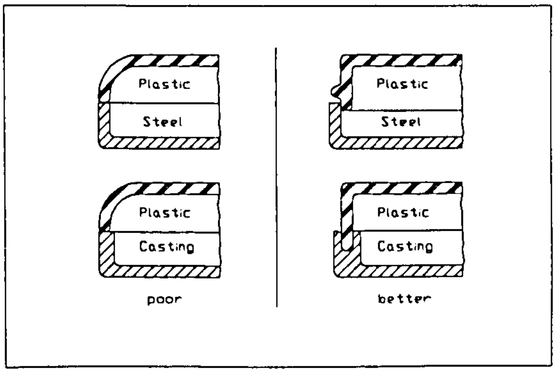
DG-IMCM-21: Irregularly shaped inserts are placed on the parting line of the mold.



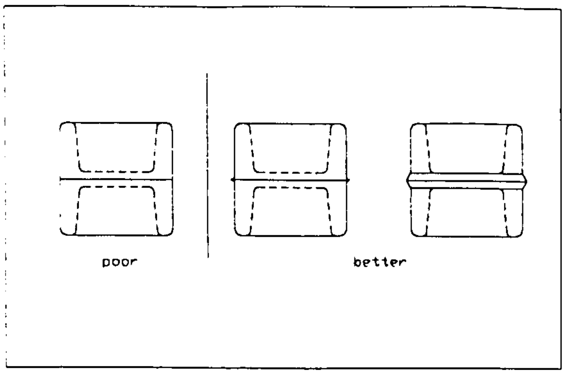
DG-IMCM-22: Recommended designs for inserts placed in plastic components.



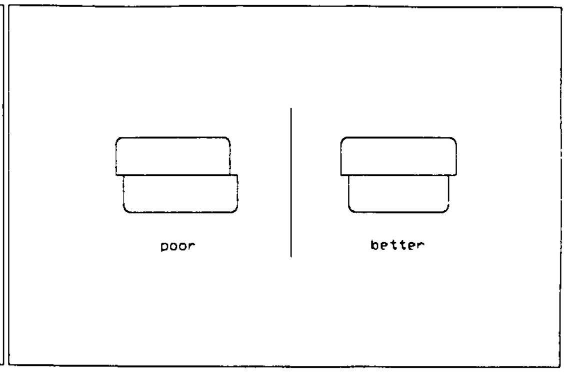
DG-IMCM-23: Provide ample material for support of inserts.



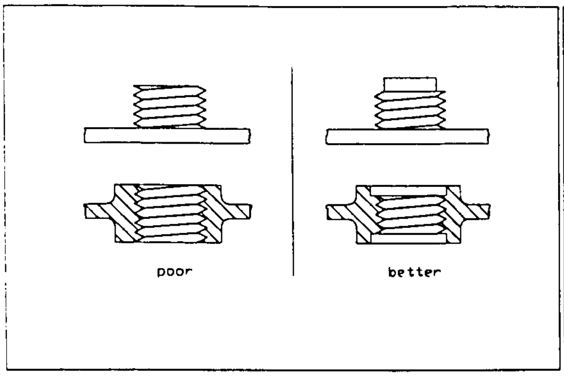
DG-IMCM-24: Lips and locating bosses aid in alignment for assembly.



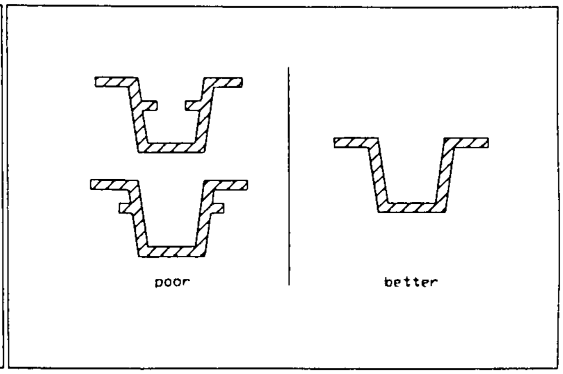
DG-IMCM-25: A bead at the parting line facilitates removal of mold flash.



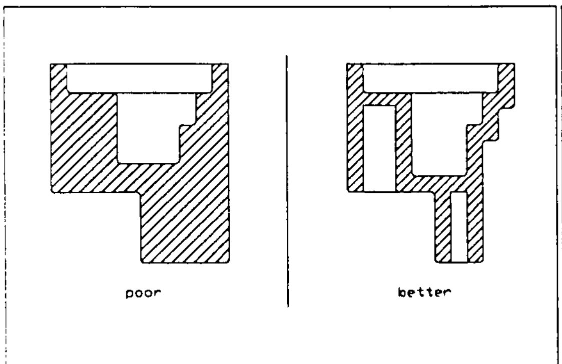
DG-IMCM-26: Deliberately offset sidewalls hide defects caused when mold halves do not line up properly.



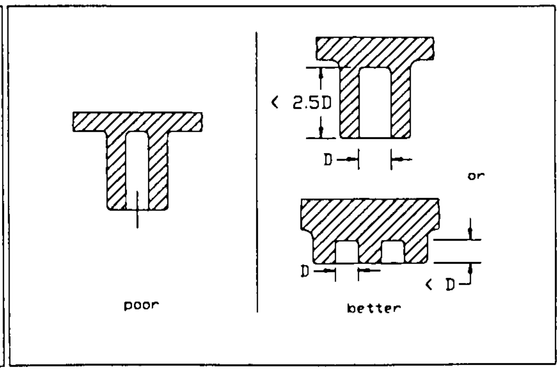
DG-IMCM-27: Screw threads should not extend to the ends of the threaded element.



DG-IMCM-28: Avoid undercuts.

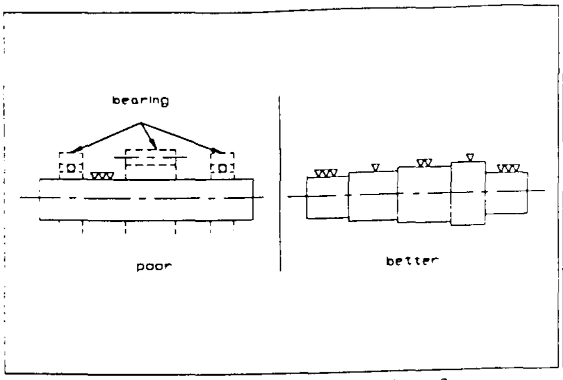


DG-IMCM-29: Maintain uniform wall thickness in thermoset parts.

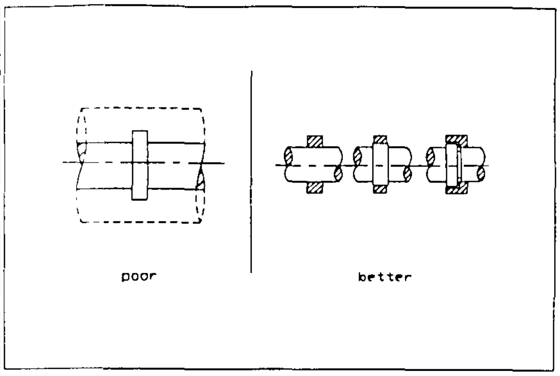


DG-IMCM-30: Depth limits for compression molded blind holes.

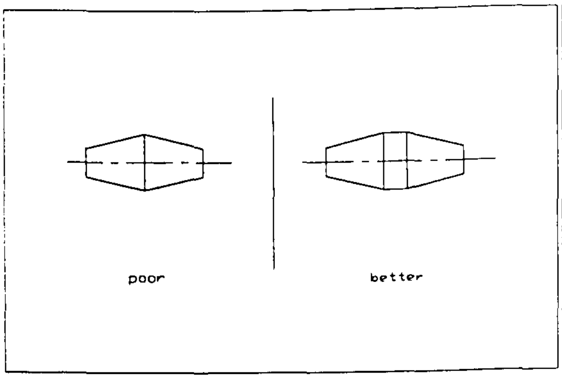
C.3 - Design Guidelines for Turning



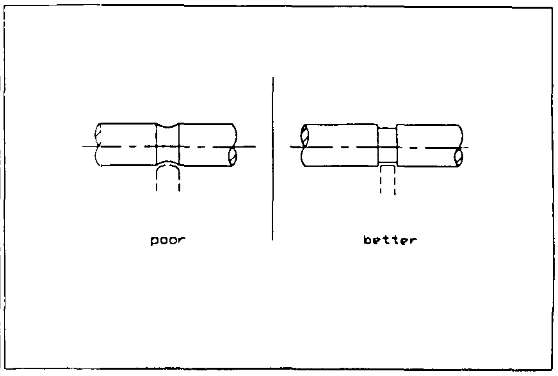
DG-T-1: Adapt working length and surface finish to the required function.



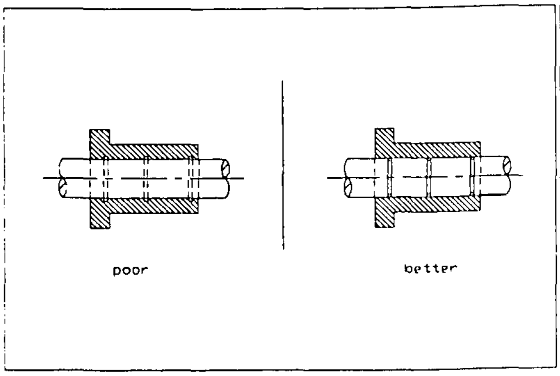
DG-T-2: Avoid excessive machining, use instead separate parts.



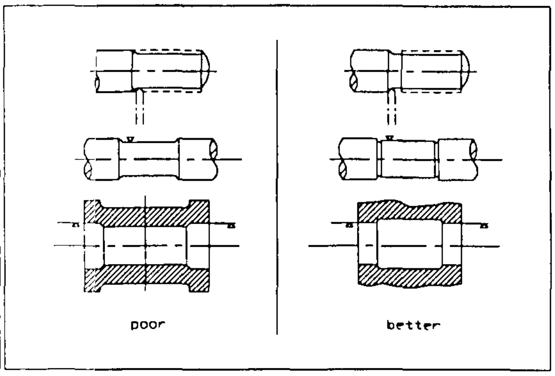
DG-T-3: Provide for adequate clamping.



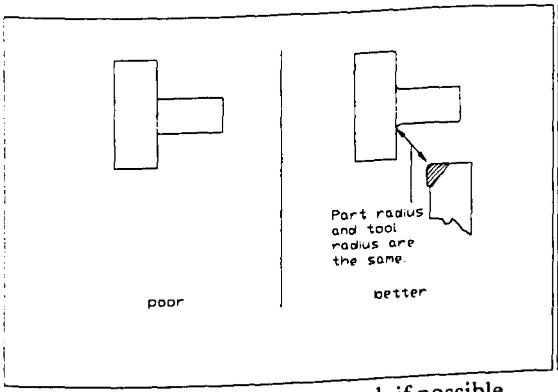
DG-T-4: Use simple tool shapes.



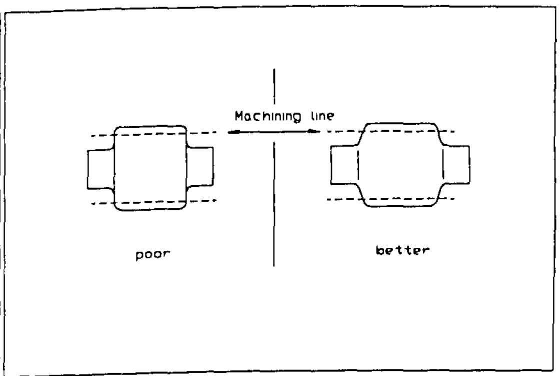
DG-T-5: Avoid grooves and tight tolerances on inner surfaces.



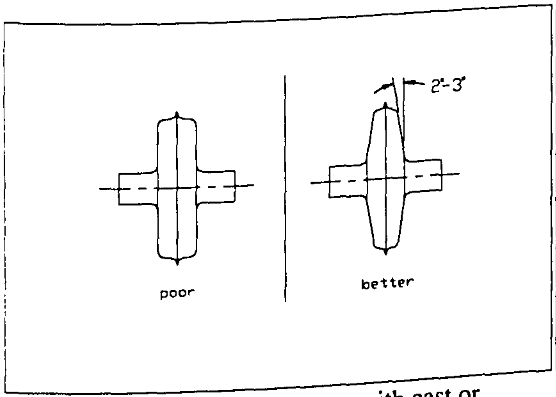
DG-T-5: Provide adequate tool runout.



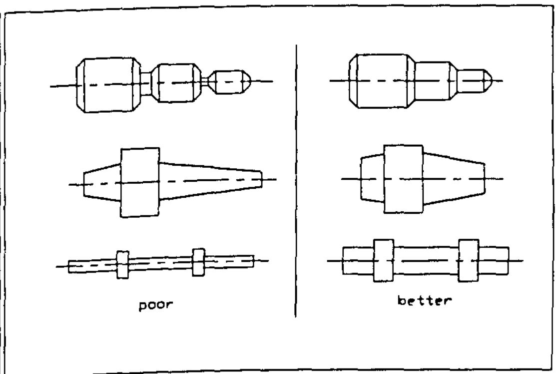
DG-T-7: Avoid sharp corners, and, if possible, leave radius dimensions to the discretion of the manufacturer.



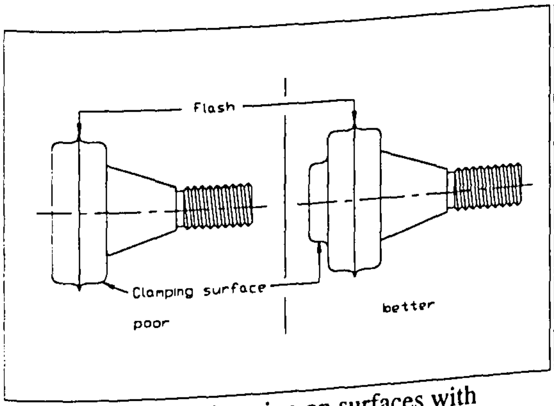
DG-T-8: Minimize sharp corners and burrs by including chamfers or curved surfaces.



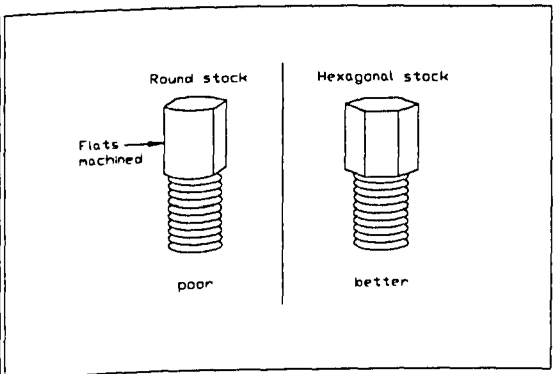
DG-T-9: Provide tool clearance with cast or forged-in relief on surfaces to be faced.



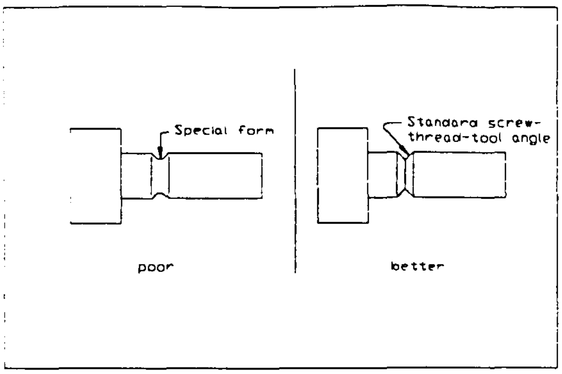
DG-T-10: In turning, keep parts short and stocky to minimize deflection.



DG-T-11: Avoid clamping on surfaces with flash.

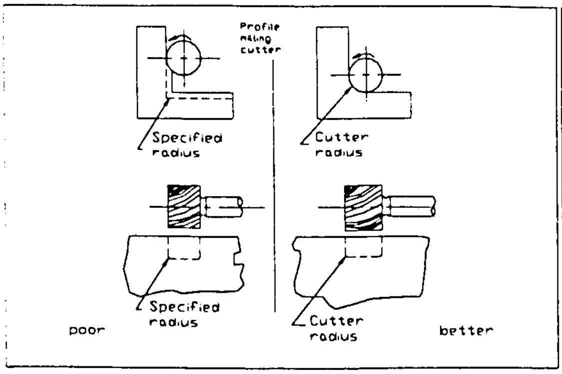


DG-T-12: Use stock shapes whenever possible.

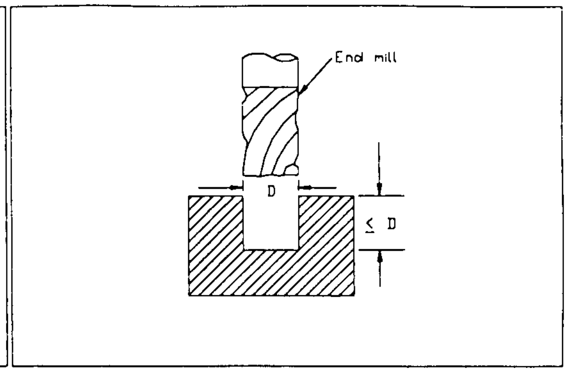


DG-T-13: Choose designs so that standard cutting tools can be used.

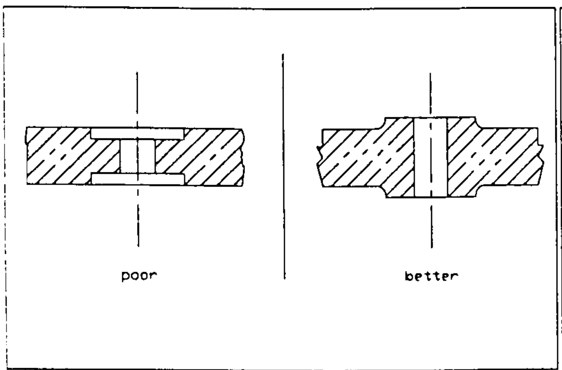
C.4 - Design Guidelines for Milling



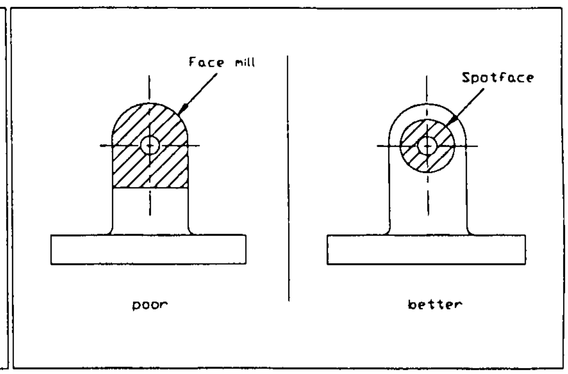
DG-M-1: Specify cutter radius whenever possible.



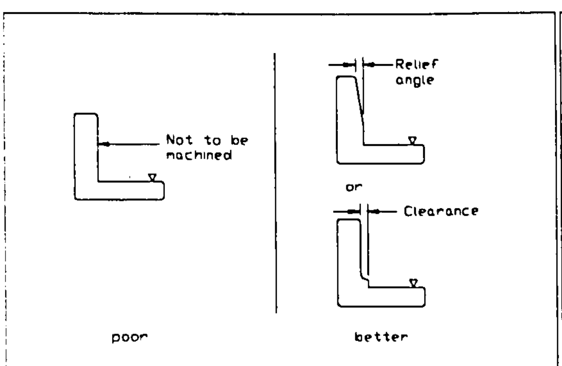
DG-M-2: End mills in steel have the depth limitation shown.



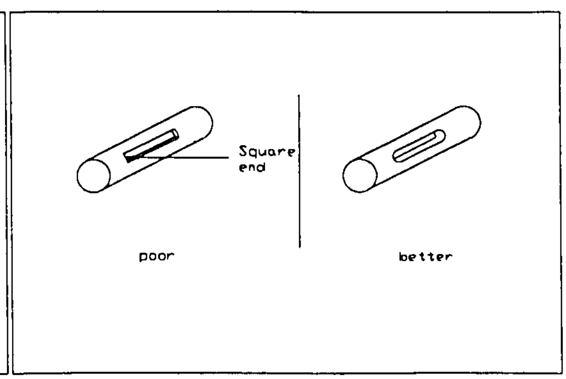
DG-M-3: Provide for flat surfaces.



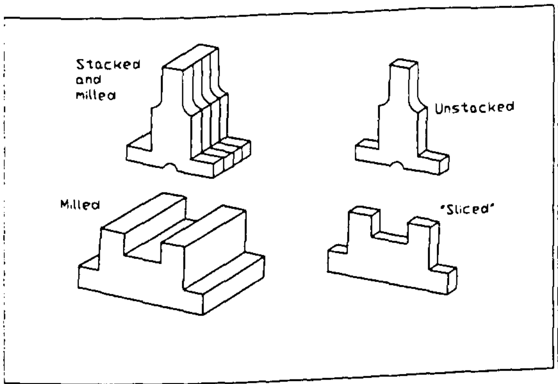
DG-M-4: For small flat surfaces, spot face rather than face mill.



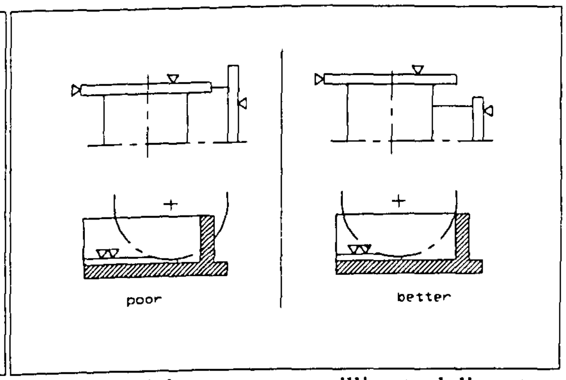
DG-M-5: Provide clearance for milling cutter



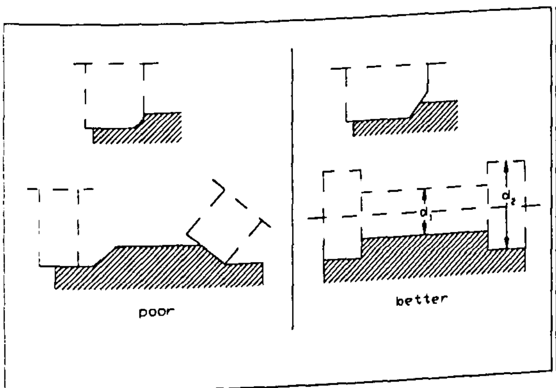
DG-M-6: Make keyways with standard cutters.



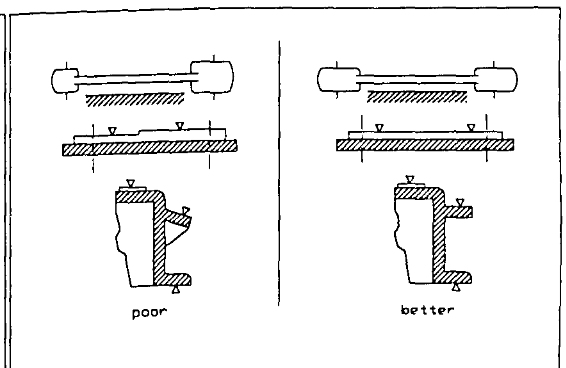
DG-M-7: Designs that permit stacking or "slicing" are often economical.



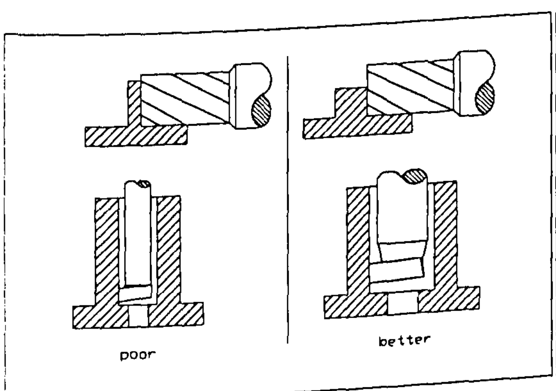
DG-M-8: Adapt runout to milling tool diameter.



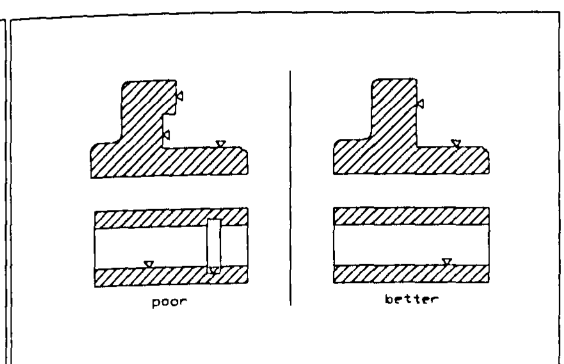
DG-M-9: Use straight milling surfaces.



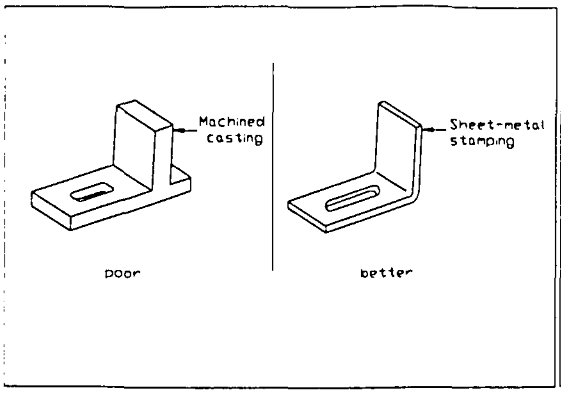
DG-M-10: Arrange surfaces on one level and parallel to the clamping surface.



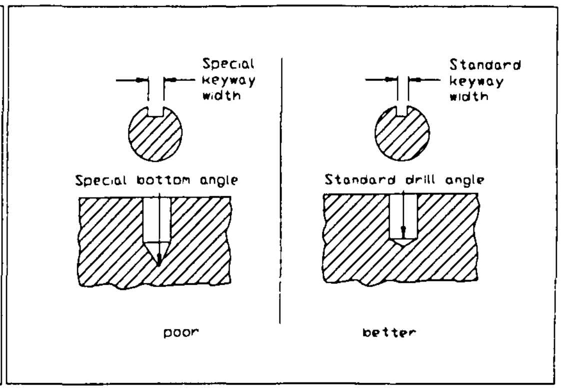
DG-M-11: Parts and tools must not deflect



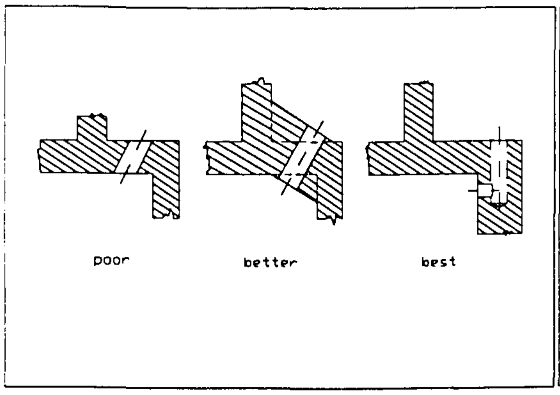
DG-M-12: Avoid undercuts.



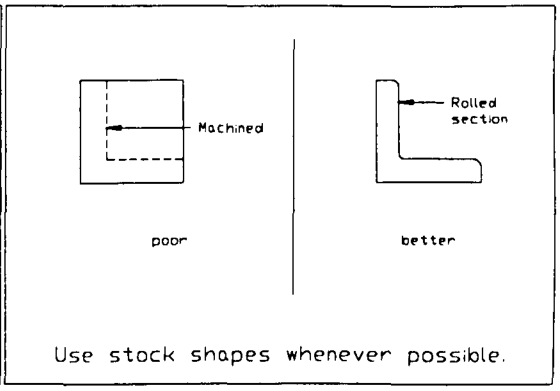
DG-M-13: Stampings are frequently less costly than machining.



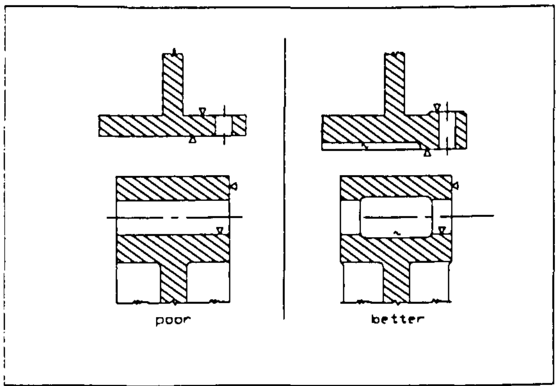
DG-M-14: Choose designs so that standard cutting tools can be used.



DG-M-15: Drilled holes should be perpendicular to surface.

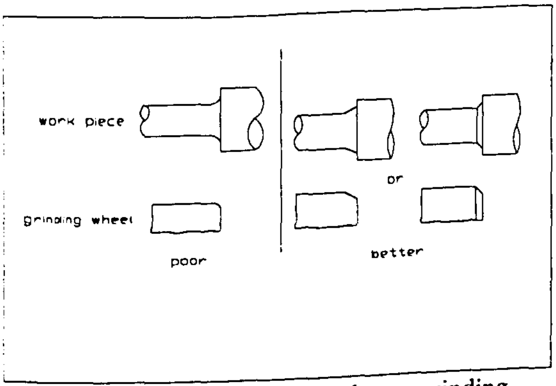


DG-M-16: Use stock shapes whereever possible.

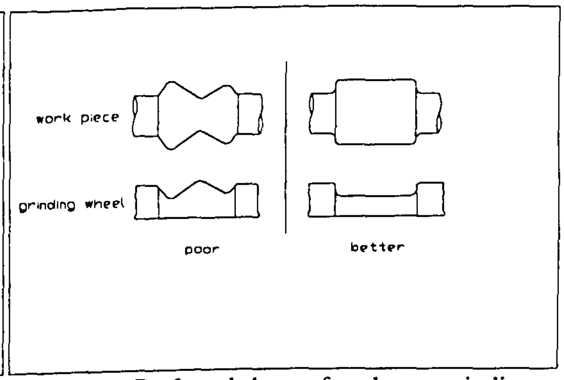


DG-M-17 Suggestions to reduce machining time.

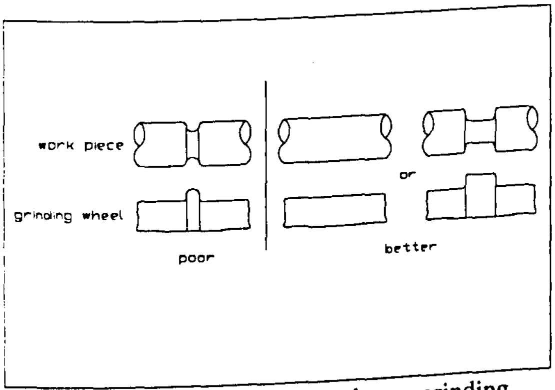
C.5 - Design Guidelines for Grinding



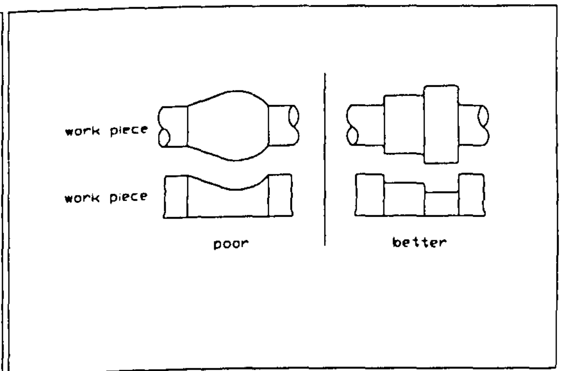
DG-G-1: Preferred shapes for plunge-grinding.



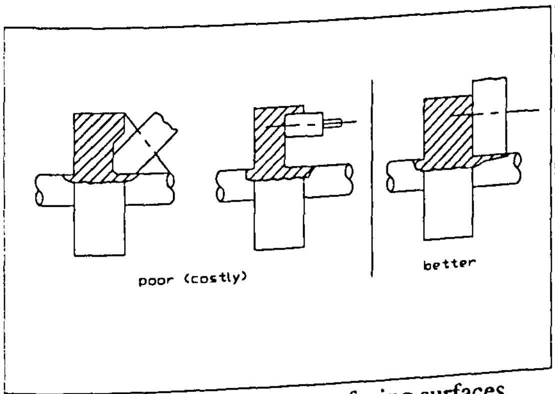
DG-G-2: Preferred shapes for plunge-grinding.



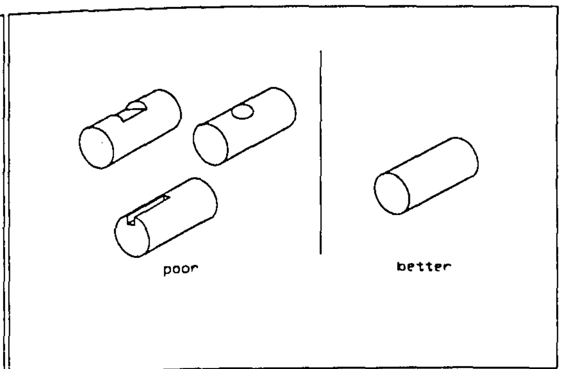
DG-G-3: Preferred shapes for plunge-grinding.



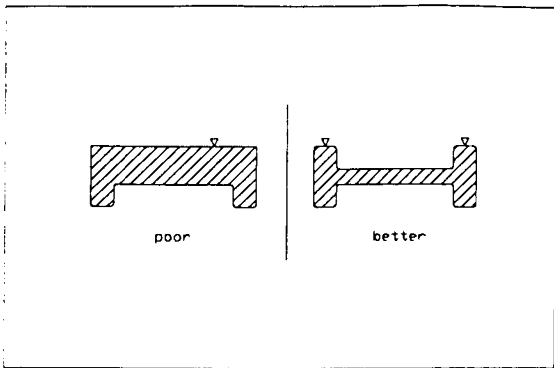
DG-G-4: Preferred shapes for plunge-grinding.



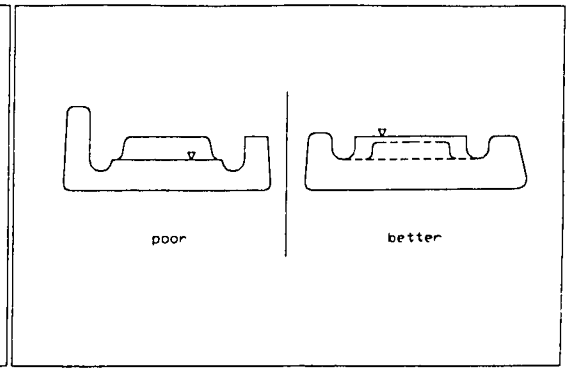
DG-G-5: Ground undercuts on facing surfaces should be avoided.



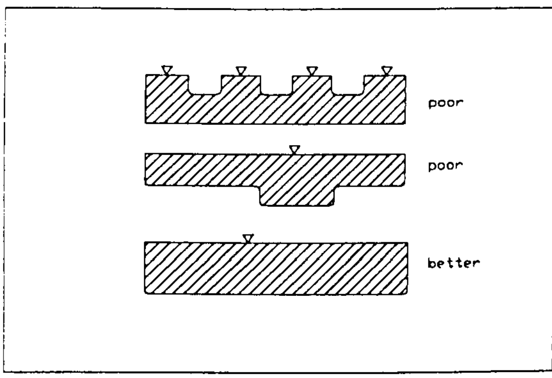
DG-G-6: Interrupted surfaces reduce the accuracy of cylindrically ground parts.



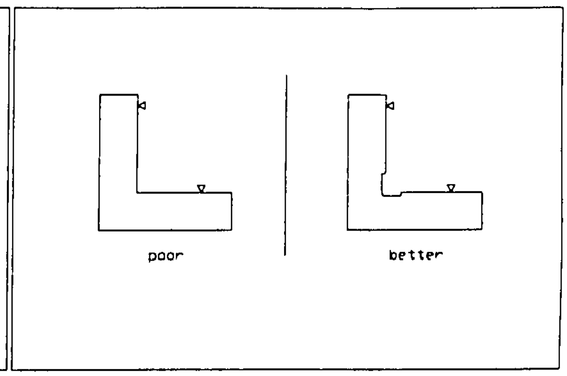
DG-G-7: Minimize surface to be ground and reduce part weight.



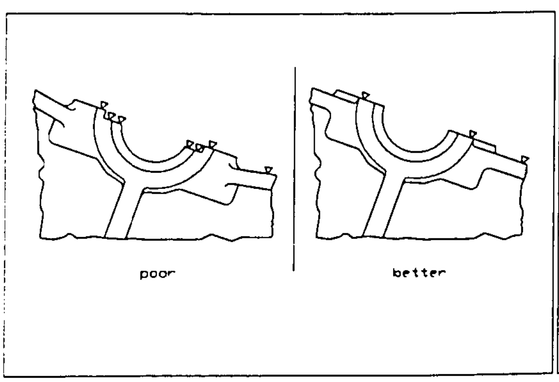
DG-G-8: Avoid surfaces higher than the surface to be ground.



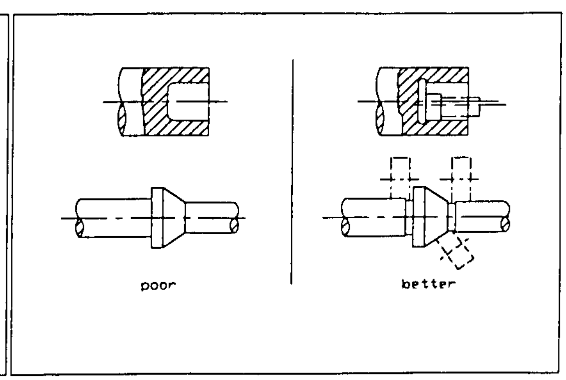
DG-G-9: If flatness is critical, avoid openings in the ground surface and poorly supported areas.



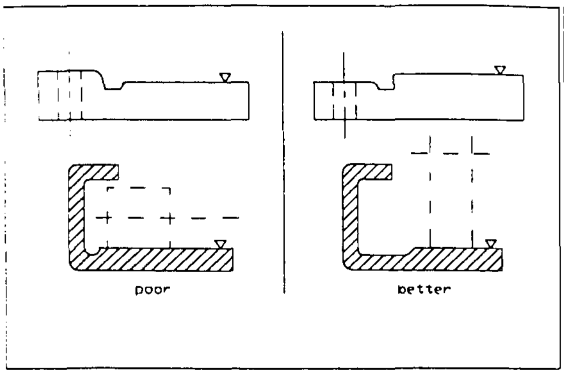
DG-G-10: Leave runout space for grinding wheels.



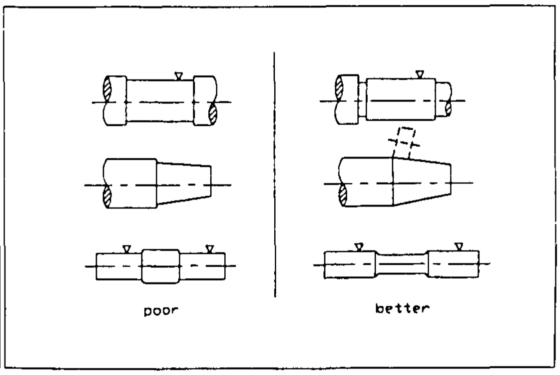
DG-G-11: Design for grinding in a single setup



DG-G-12: Provide runouts for grinding wheels.

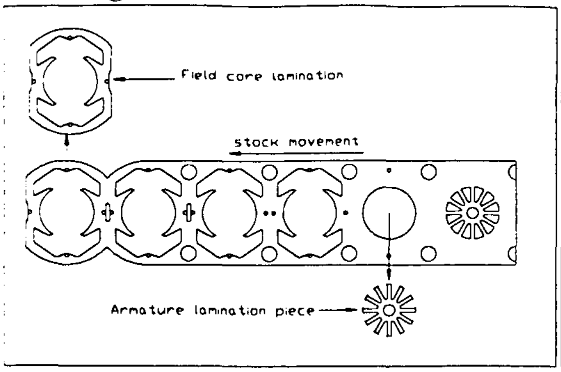


DG-G-13: Aim for unimpeded grinding.

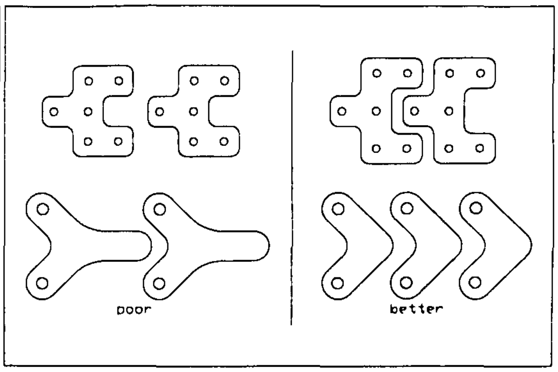


DG-G-14: Avoid edge limitations for grinding wheels.

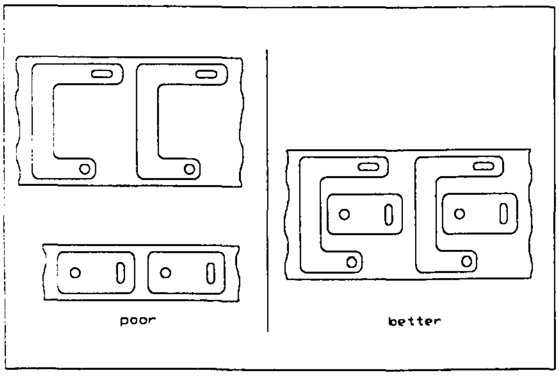
C.6- Design Guidelines for Sheet Metal Working



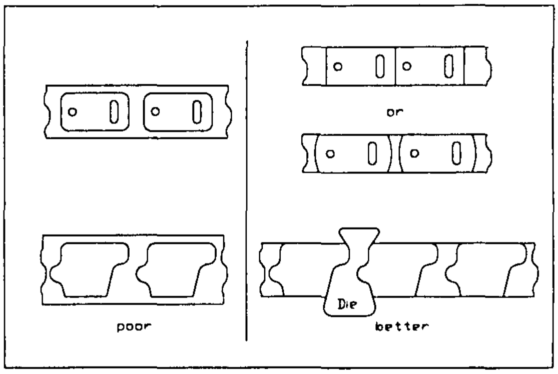
DG-SM-1: Die blanking sequence for motor laminations.



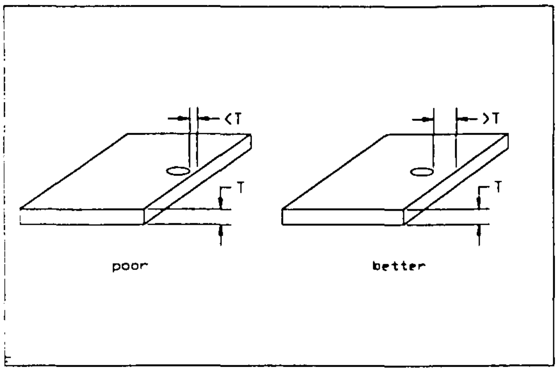
DG-SM-2: Part redesign can improve material utilization.



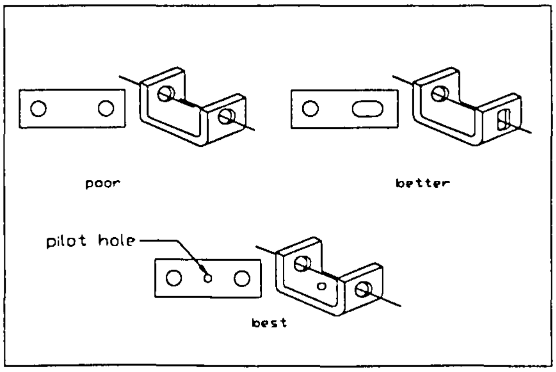
DG-SM-3: Combine parts to improve material utilization.



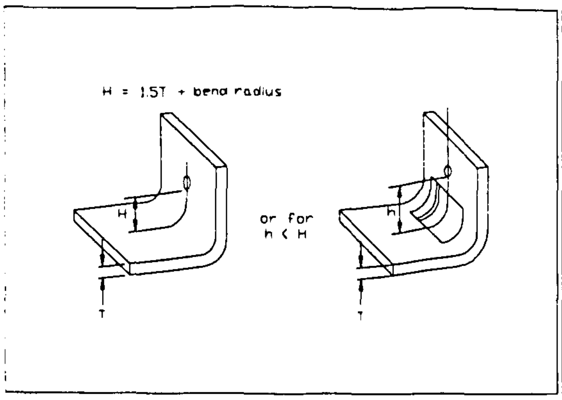
DG-SM-4: Use width of stock to improve material utilization.



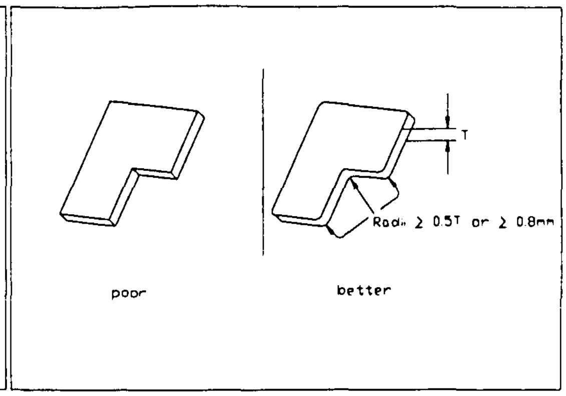
DG-SM-5: Design rules for holes near a boundary



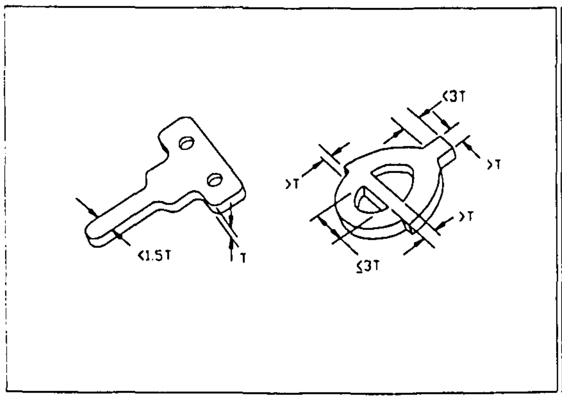
DG-SM-6: Means of avoiding alignment problems in parts.



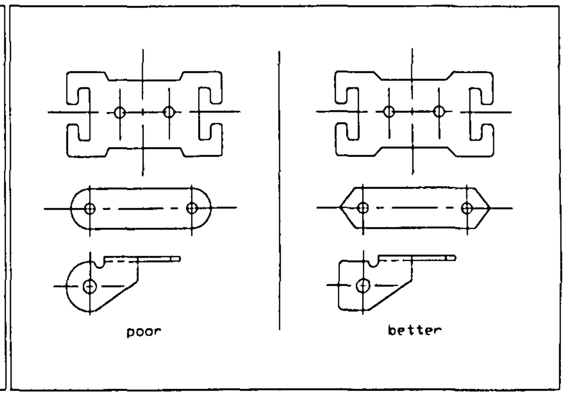
DG-SM-7: Minimum spacing to avoid distortion of a hole.



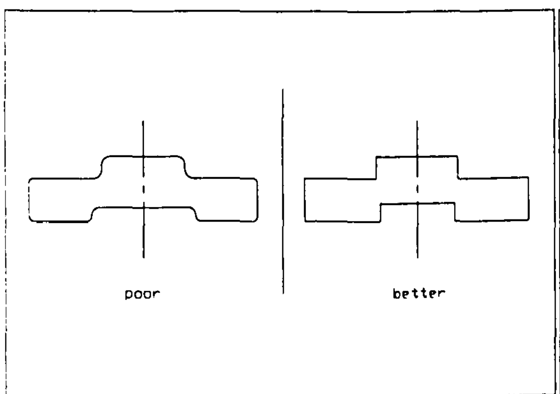
DG-SM-8: Guidelines for fillets and radii of blanked parts.



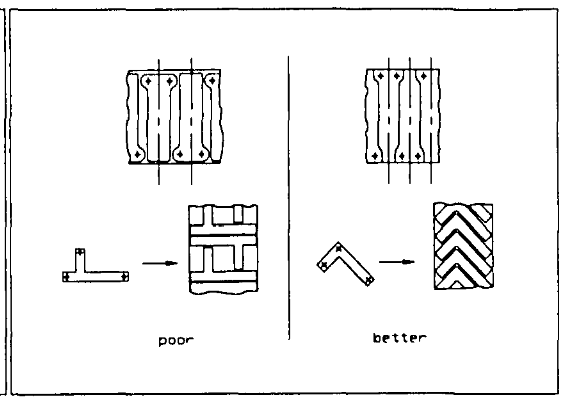
DG-SM-9: Avoid narrow projections and webs.



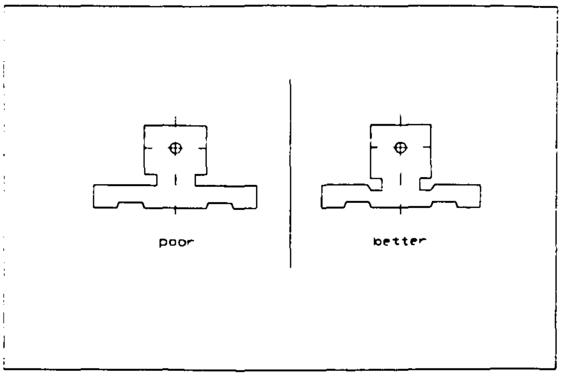
DG-SM-10: Design for simple cuts and angular corners; avoid curves.



DG-SM-11: Design for sharp-edged transitions, which ensures easy grinding.

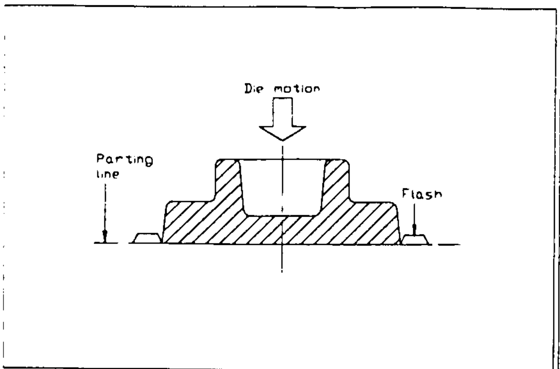


DG-SM-12: Avoid waste by careful layout and part design.

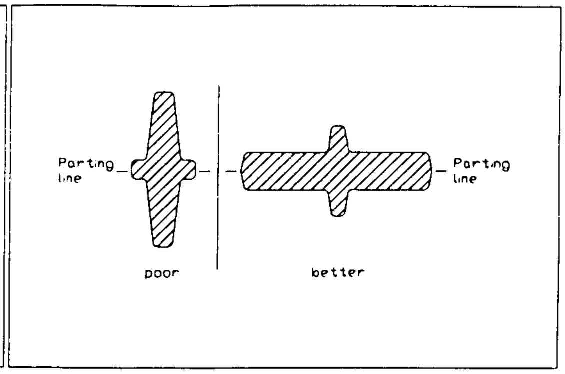


DG-SM-13: Design for shapes that permit subsequent cuts without danger of damage to other features.

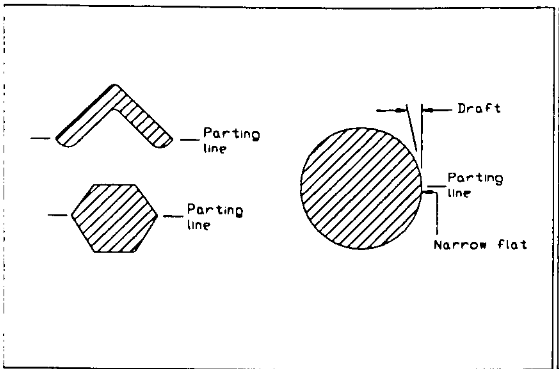
C.7 - Design Guidelines for Forging



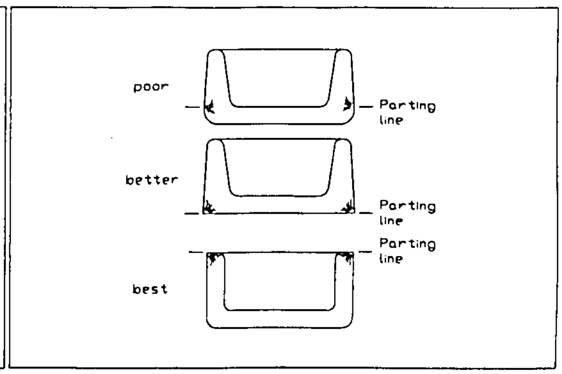
DG-F-1: Choose parting lines such that the part lies entirely in one die half.



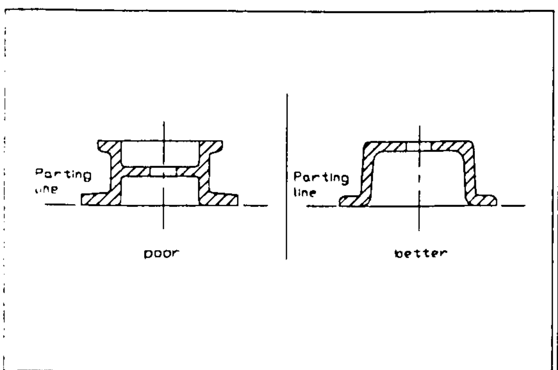
DG-F-2: Locate parting line so that metal will flow parallel to the parting line.



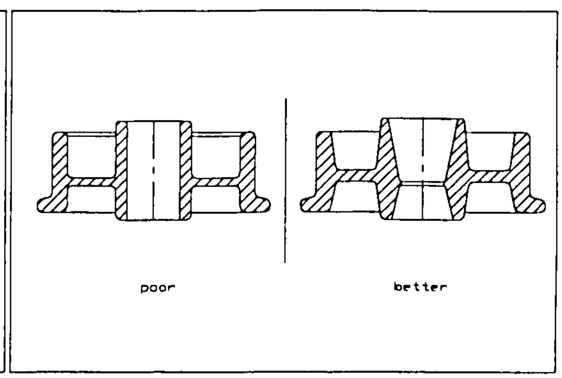
DG-F-3: Some shapes have natural parting lines.



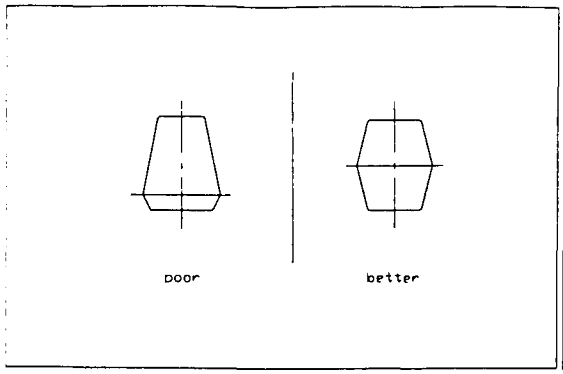
DG-F-4: Preferred parting line location where flash can occur.



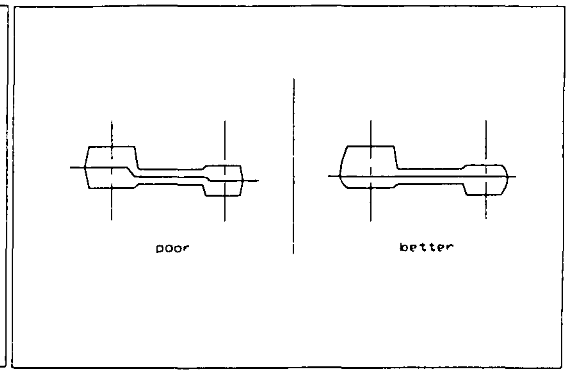
DG-F-5: Avoid undercuts.



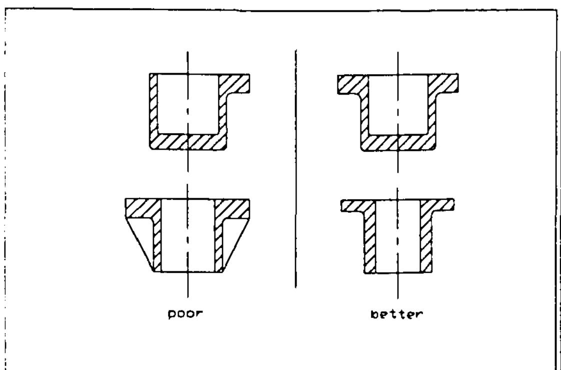
DG-F-6: Provide tapers.



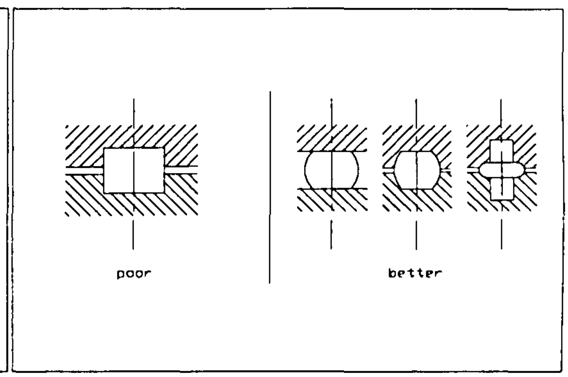
DG-F-7: Design for parting lines at about half height.



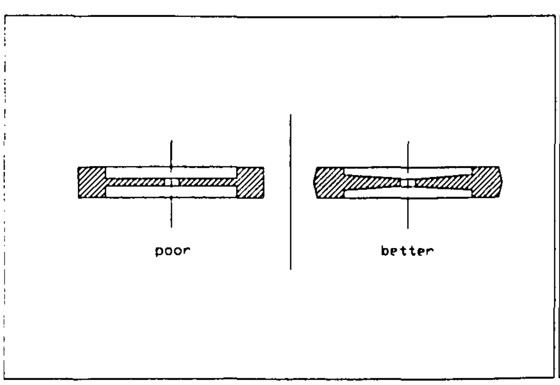
DG-F-8: Avoid non-planar parting lines.



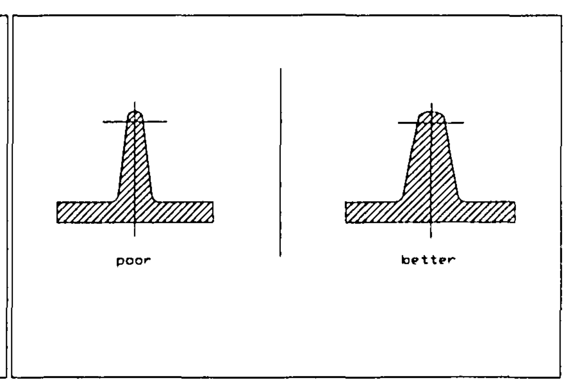
DG-F-9: Design for rotationally symmetrical parts.



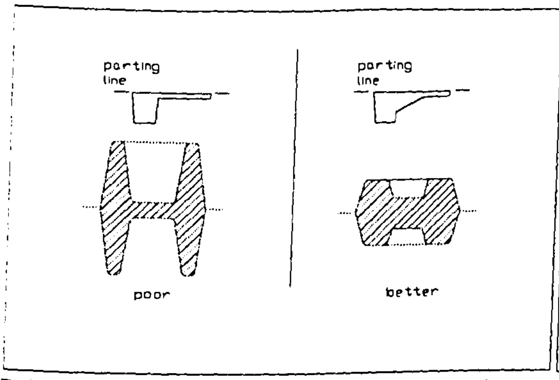
DG-F-10: Design for shapes that occur during unrestrained pressing.



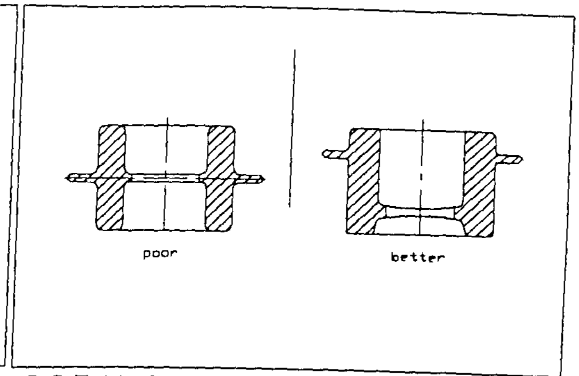
DG-F-11: Avoid excessively thin sections.



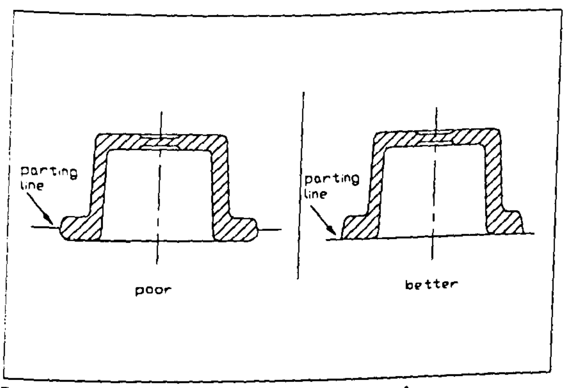
DG-F-12: Avoid large curvatures, excessively narrow ribs, fillets and small holes.



DG-F-13: Avoid sharp changes in cross sections and cross sections that project excessively into the die.

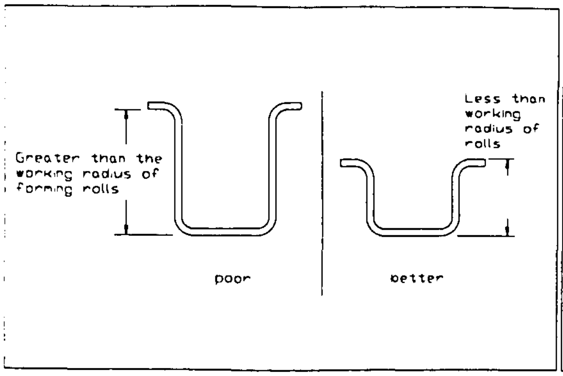


DG-F-14: Stagger parting lines in the case of cup-shaped parts of large depth.

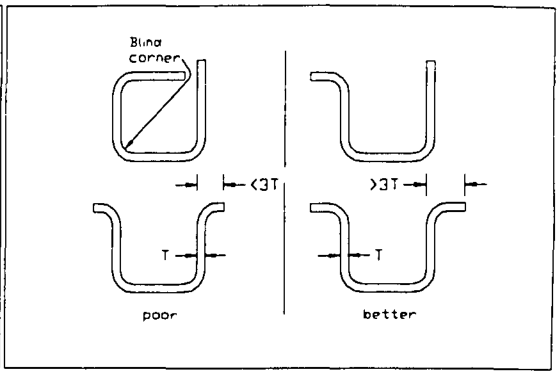


DG-F-15: Select the parting line so that misalignment is easily detected and removal of flash is simple.

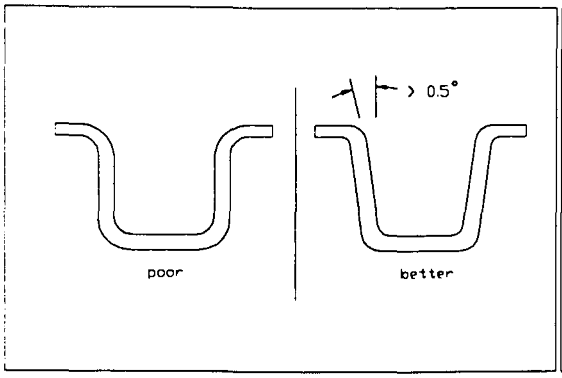
C.8 - Design Guidelines for Rolling



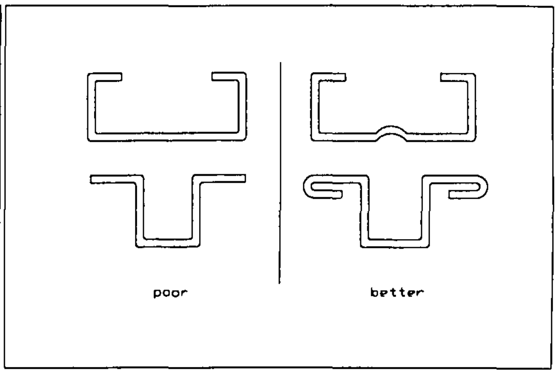
DG-R-1: Keep depth of roll-formed section as small as possible.



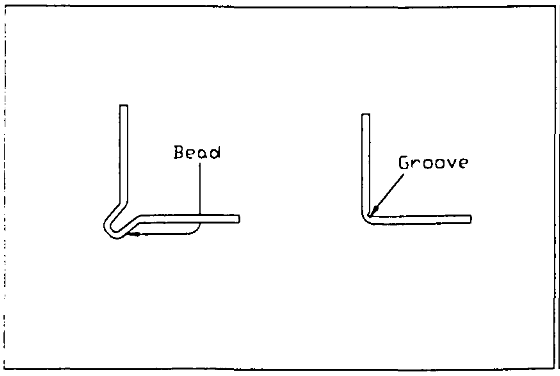
DG-R-2: Avoid blind corners and provide for sufficient "leg" length.



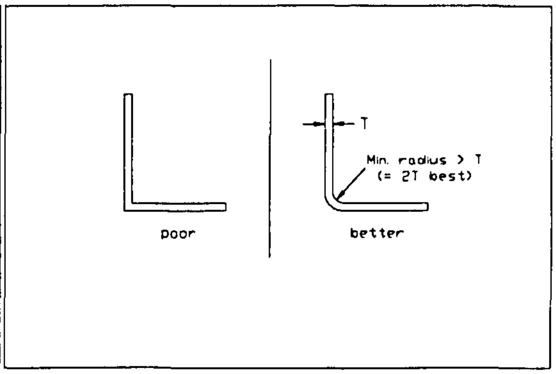
DG-R-3: Provide for slight draft angle.



DG-R-4: Provide stiffening bends to avoid waviness in wide areas and near edges.

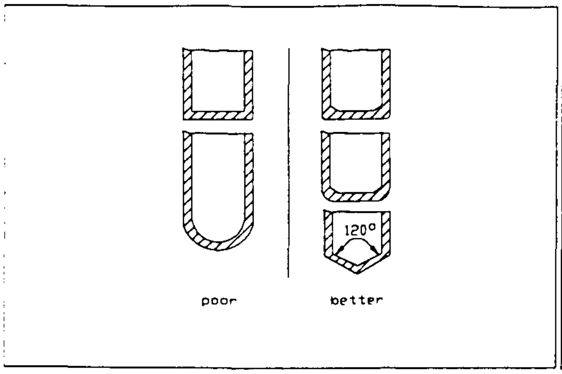


DG-R-5: Two means of achieving sharp corners in roll-formed parts.

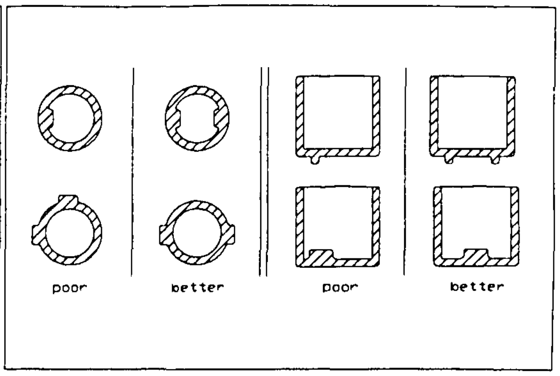


DG-R-6: Provide minimum-bend radius for thin roll-formed components.

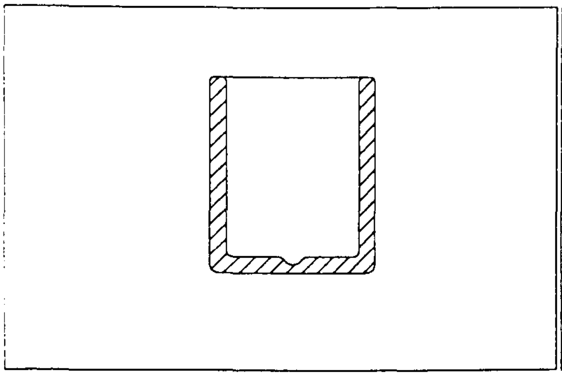
C.9 - Design Guidelines for Extrusion



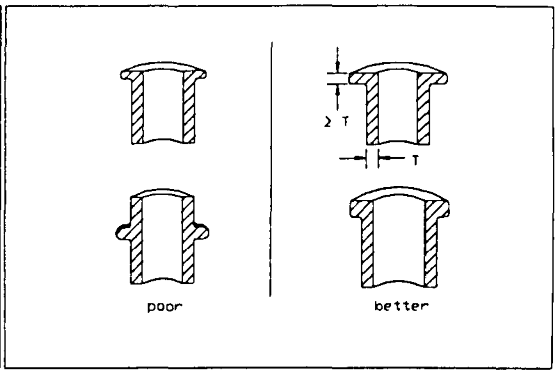
DG-E-1: For backward extrusion, use inclined bottom surface, rounded outside corners and sharp inside corners.



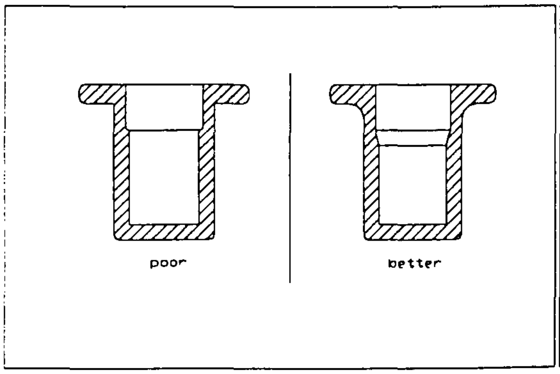
DG-E-2: Impact-extruded parts should be symmetrical.



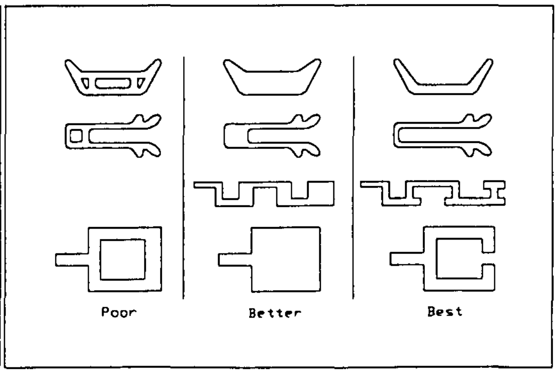
DG-E-3: Provide recess in bottom of part to minimize floating of the punch, and ensure uniform wall thickness.



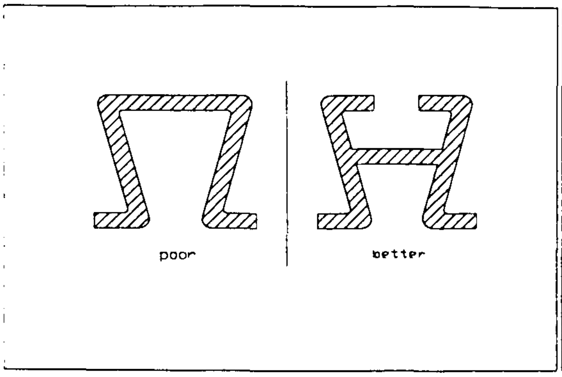
DG-E-4: Flanges should be at least as thick as the sidewall and be located at or near the ends of the forward extrusion.



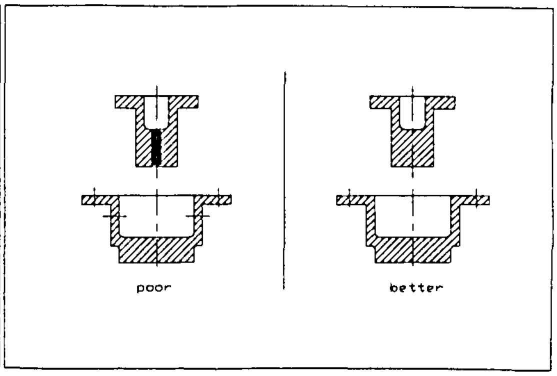
DG-E-5: Forward extrusions should have external fillets, but bottom corners can be sharp.



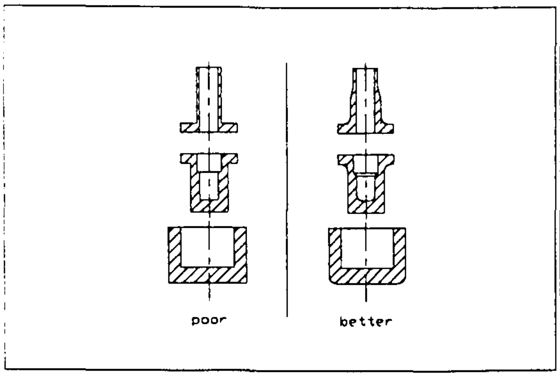
DG-E-6: Avoid hollows and maintain uniform wall profiles.



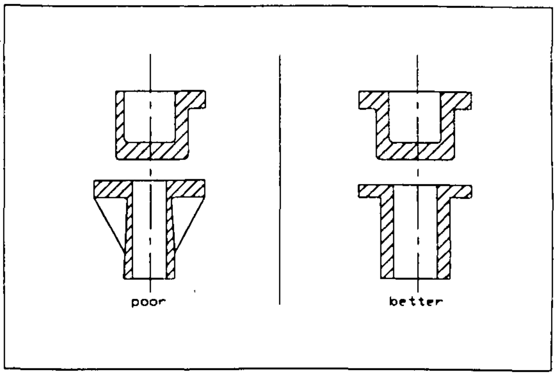
DG-E-7: Ensure that die members are sufficinetly strong.



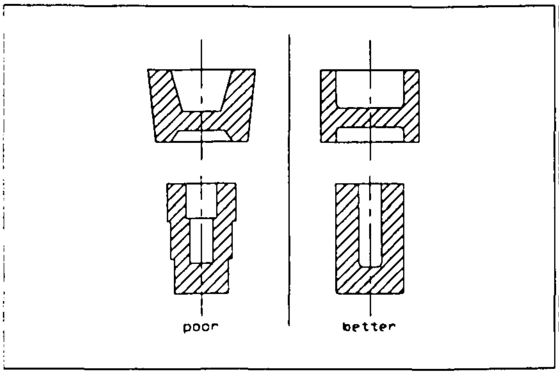
DG-E-8: Avoid small, long or lateral holes and threads.



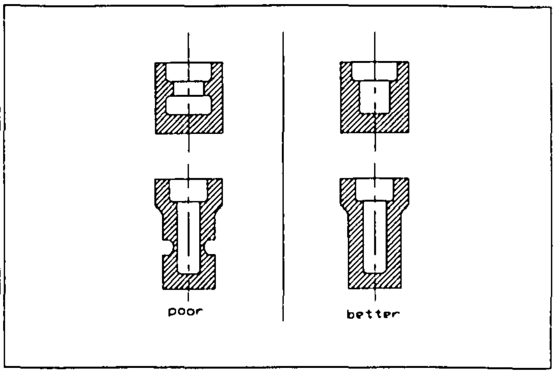
DG-E-9: Avoid sharp changes in cross section, sharp edges and fillets.



DG-E-10: Provide rotationally symmetrical parts without material protrusions.

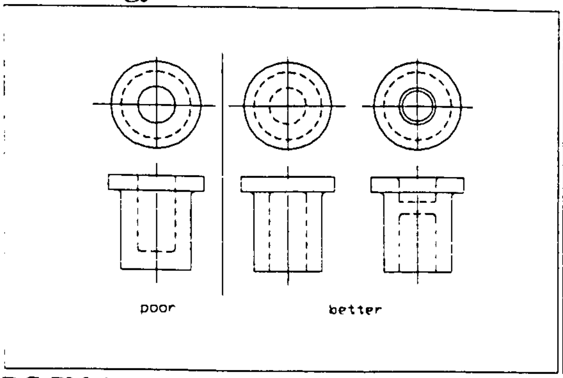


DG-E-11: Avoid tapers and almost equal diameters

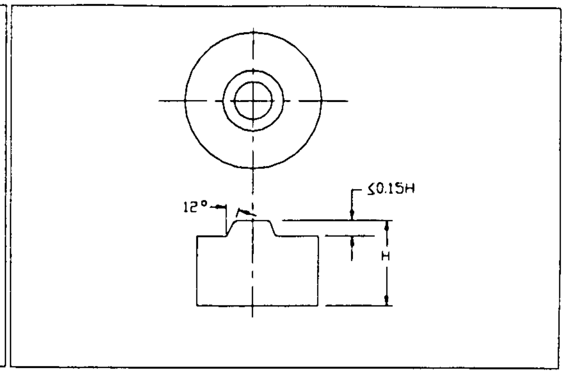


DG-E-12: Avoid undercuts.

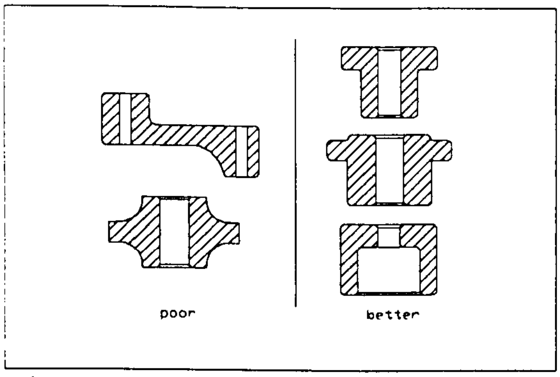
C.10 - Design Guidelines for Powder Metallurgy



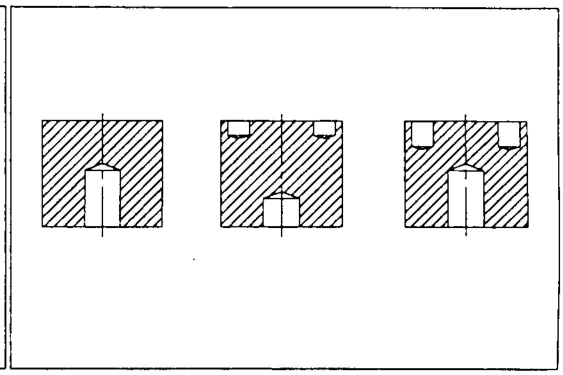
DG-PM-1: Avoid blind holes with the blind end opposite a flange.



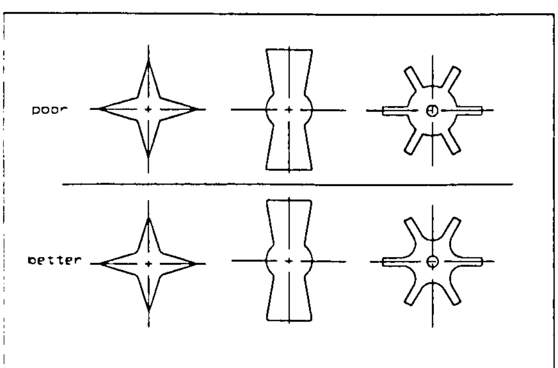
DG-PM-2: A boss can be formed in the punch face if these guidelines are observed.



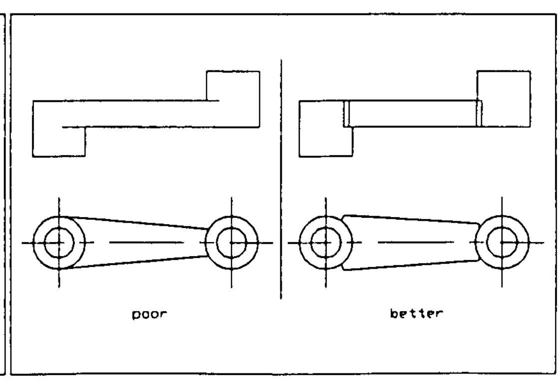
DG-PM-3: Smaller radii are preferred.



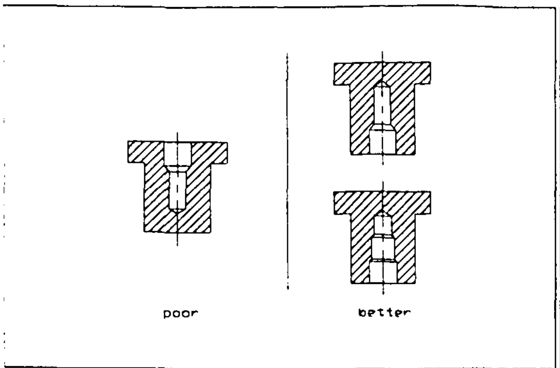
DG-PM-4: Blind holes on bottom may be deep, those on top shallow.



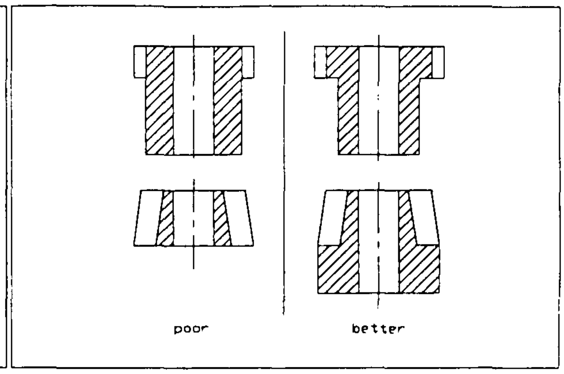
DG-PM-5: Use rounded corners in horizontal cross-sections.



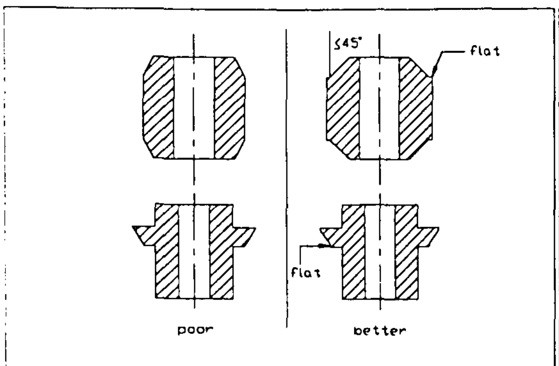
DG-PM-6: Avoid feathered edges.



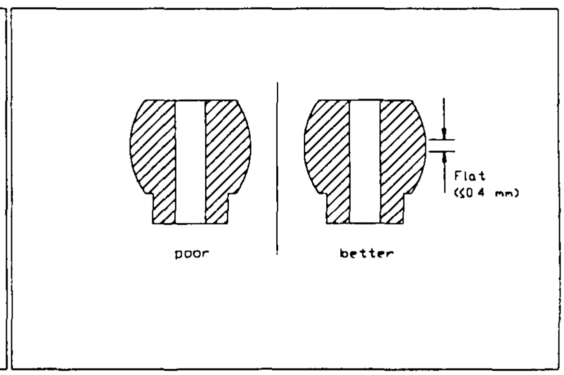
DG-PM-7: Orientation of stepped blind holes; however, large-diameter uniform holes are preferred.



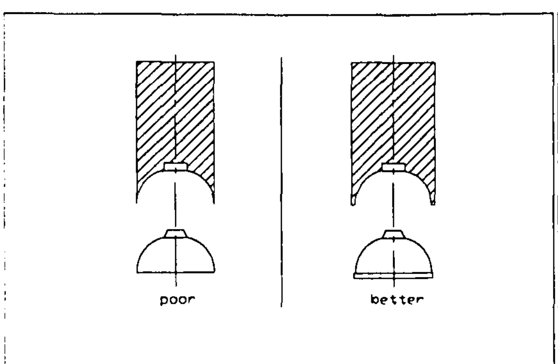
DG-PM-8: Recommended designs for gears.



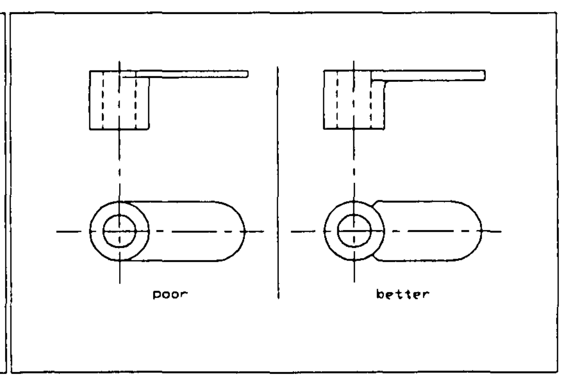
DG-PM-9: Guidelines for angled sidewalls.



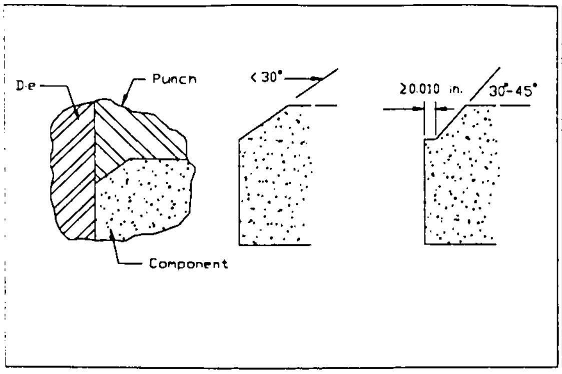
DG-PM-10: Guidelines for spherical surfaces.



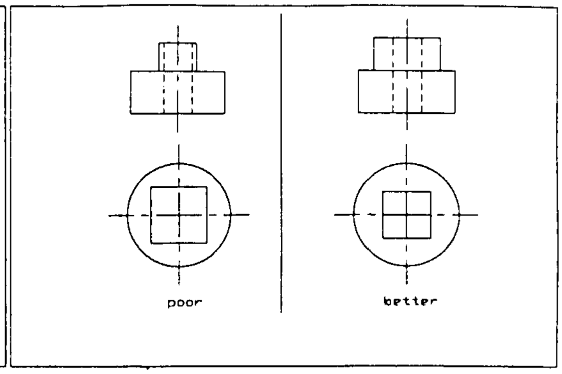
DG-PM-11: Use flat to avoid a feather edge.



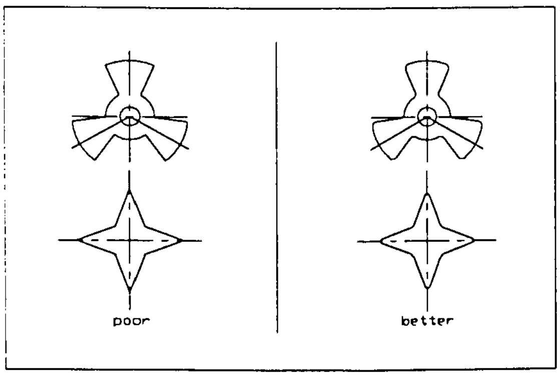
DG-PM-12: Make thin protrusions as thick as possible and joined to more massive portions with generous radii.



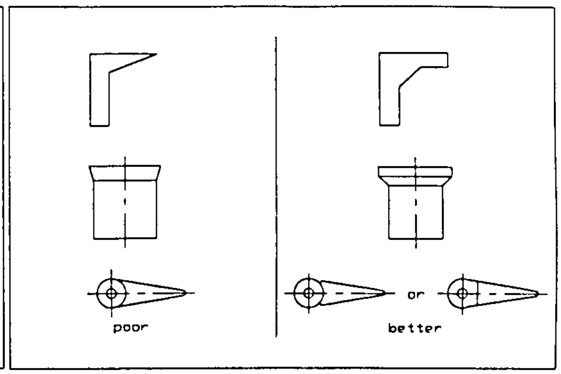
DG-PM-13: Use a chamfer or a chamfer and flat at the intersection of tool members.



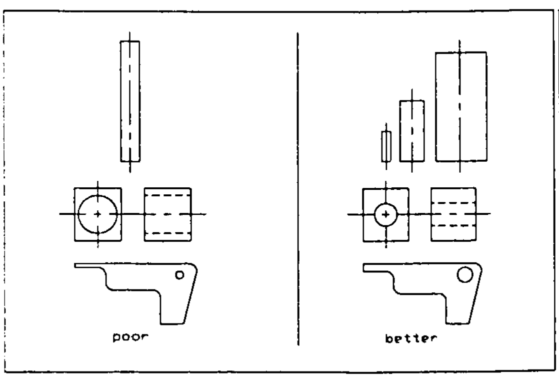
DG-PM-14: Avoid abrupt changes in mass and thin walls.



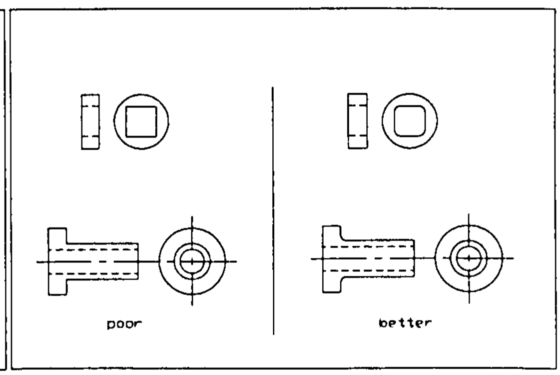
DG-PM-15: Avoid sharp interior corners and feather edges.



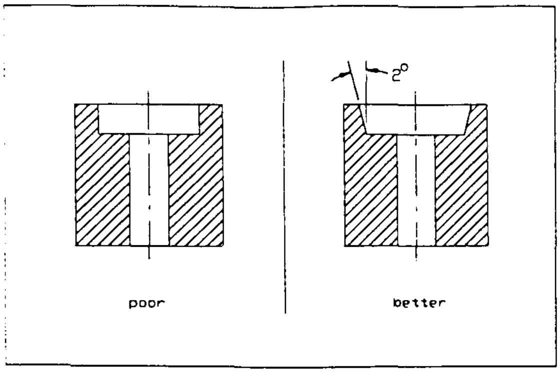
DG-PM-16: Avoid sharp interior corners and feather edges.



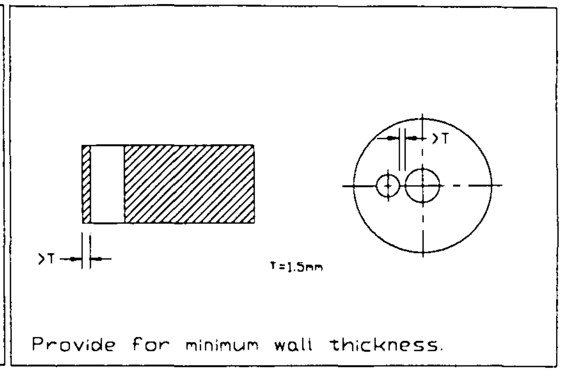
DG-PM-17: Observe recommended minimum dimensions.



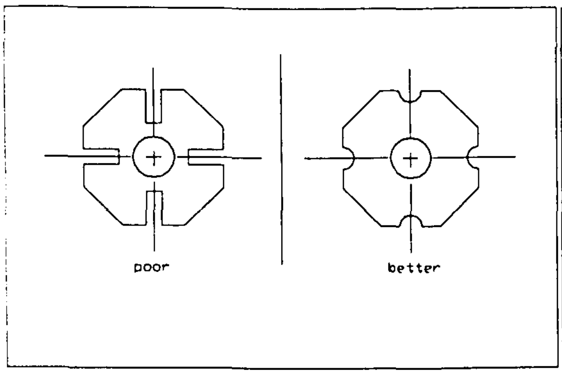
DG-PM-18: Avoid sharp corners ans sharp re-entry corners.



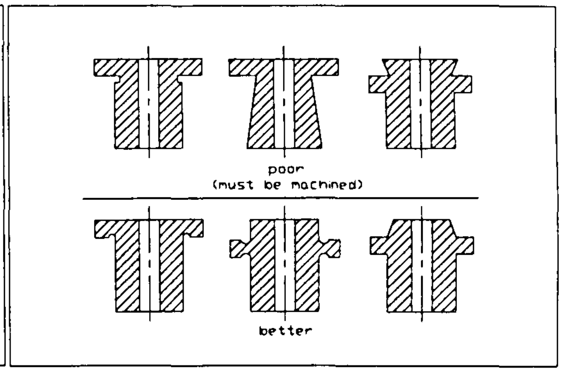
DG-PM-19: Provide draft for recess on top of part.



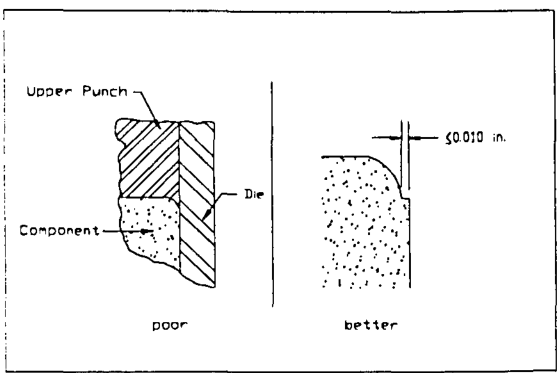
DG-PM-20: Provide for minimum wall thickness.



DG-PM-21: Avoid long thin tooling members.



DG-PM-22: Avoid undercuts.



DG-PM-22: Use flats to avoid feather edge on punch.

APPENDIX D

MATERIAL SELECTION

PART I FERROUS ALLOYS

D.1 Plain Carbon Steels

Steel is considered a carbon steel when no minimum content is specified or required for chromium, cobalt, columbium (niobium), molybdenum, nickel, titanium, tungsten, vanadium or zirconium. Variations in the carbon content have the greatest effect on the mechanical properties, with increasing carbon content leading to increased hardness and strength. Carbon steels are generally categorized according to their content. Carbon steels contain up to 2% total alloying elements and can be subdivided into low-carbon steels, medium-carbon-steels, high-carbon steels, and ultra-high-carbon steels.

Low-carbon steels contain up to 0.3% carbon. The largest category of this class of steel is flat-rolled products (sheet or strip) usually in the cold-rolled and the annealed condition. The carbon content for these high-formability steels is very low, less than 0.10% carbon, with up to 0.4% manganese. Typical uses are in automobile-body panels, tin plate, and wire products. For rolled steel structural plates and sections, the carbon content may be increased to approximately 0.30%, with higher manganese contents, up to 1.5%. These latter materials may be used for stampings, forgings, seamless tubes, and boiler plates.

Medium-carbon steels are similar to low-carbon steels except that the carbon ranges from 0.30% to 0.60% and the manganese ranges from 0.60% to 1.65%. Increasing the carbon content to approximately 0.5% with an accompanying increase in manganese allows medium-carbon steels to be used in the quenched and tempered condition. The uses of medium-carbon manganese steels include shafts, couplings, crankshafts, axles, gears, and forgings. Steels in the 0.40% to 0.60% carbon range are also used for rails, railway wheels, and rail axles.

High-carbon steels contain from 0.60% to 1.00% carbon with manganese contents ranging from 0.30% to 0.90%. High-carbon steels are used to form spring materials and high-strength wires.

Ultra-high-carbon steels are experimental alloys containing approximately 1.25% to 2.0% carbon. These steels are thermomechanically processed to obtain microstructures that lead to superplastic behavior.

D.2 Alloy Steels

D.2.1 Low Alloy Steels

Low-alloy steels constitute a category of ferrous materials that exhibit mechanical properties superior to plain carbon steel as a result of additions of alloying elements such as nickel, chromium, and molybdenum. The total alloy content can range from 2.0% up to levels just below that of stainless steels, which contain a minimum of 10% chromium. The primary function of the alloying elements, in most low-alloy steels, is to increase hardenability in order to optimize mechanical properties and toughness after heat treatment. In some cases, however, alloy additions are used to reduce environmental degradation under certain specified service conditions.

The four major groups of alloy steels are:

- Low-carbon quenched and tempered steels, which combine high yield strength and high tensile strength with good notch toughness, ductility, corrosion resistance, or weldability. The various steels that fall under this group have different combinations of these characteristics based on their intended applications.
- Medium-carbon ultra-high-strength steels, which are structural steels with yield strengths that can exceed 200,000 psi (1,380 MPa). The product forms of this steel include billet, bar, rod, forgings, sheet, tubing, and welding wire.
- Bearing steels, which are used for ball and roller bearing applications and are comprised of low-carbon (0.10% to 0.20% carbon) case-hardened steels and high-carbon (~ 1.0% carbon) through-hardened steels.
- Chromium-molybdenum heat-resistant steels, which contain 0.5 to 9% chromium and 0.5% to 2.0% molybdenum. The carbon content is usually below 0.20%. The chromium provides improved oxidation and corrosion resistance, and the molybdenum increases the strength at elevated temperatures. Chromium-molybdenum steels are widely used in the oil and gas industries and in fossil fuel and nuclear power plants.

High-strength low-alloy steels, or microalloyed steels, are designed to provide better mechanical properties and/or greater resistance to atmospheric corrosion than conventional carbon steels. They are not considered to be alloy steels because they are designed to meet specific mechanical properties rather than a chemical composition. These steels have low carbon contents (between 0.05% and 0.25%) in order to produce adequate formability and weldability, and they have manganese contents up to 2.0%. Small quantities of chromium, nickel, molybdenum, copper, nitrogen, vanadium, niobium, titanium, and zirconium are used in various combinations. Primary applications for high-strength low-alloy steels include oil and gas line pipe, ships, offshore structures, automobiles, off-highway equipment, and pressure vessels. High-strength low-alloy steel castings are used in machine tools; high-speed transportation units; steam turbines; valves and fittings; railway, automotive, excavating, and chemical processing equipment; pulp and paper machinery; refinery equipment; rayon machinery; and various types of marine equipment.

D.2.2 Tools Steels

A tool steel is any steel used to make tools for cutting, forming, or otherwise shaping a material into a part or component adapted to a definite use. These complex alloy tool steels, which contain relatively large amounts of tungsten, molybdenum, vanadium, manganese, and chromium, make it possible to meet increasingly severe service demands and to provide greater dimensional control and freedom from cracking during heat treatment. Many alloy tool steels are also widely used for machinery components and structural applications in which particularly stringent requirements must be met, as in high-temperature springs, ultrahigh-strength fasteners, special-purpose valves, and bearings of various types for elevated-temperature service. In many applications, tool steels must

be able to withstand extremely high loads as well as to resist wear.

Most tool steels are wrought products, but precision castings can be used to advantage in some applications. The powder metallurgy process is also used in making tool steels. It provides a more uniform carbide size and distribution in large sections while allowing special compositions that cannot be obtained otherwise. Powder metallurgy tool steels are used in milling cutters, reamers, taps, drills, broaching tools, and gear hobs. They perform much better than wrought tool steels, in that, they can operate at much higher cutting speeds and they have a much longer life.

The different classes of tool steels that are used are:

High-speed steels: High-speed steels are tool steels developed largely for use in high-speed cutting applications. There are two classes of high-speed tool steels, the molybdenum high-speed steels and the tungsten high-speed steels. Both the classes of high-speed tool steels are used in cutting tools such as drills, reamers, end mills, milling cutters, taps and hobs; cold-work applications such as cold-header die inserts, thread-rolling dies, punches, and blanking dies. The tungsten steels perform better in hardening conditions and are used in these cases.

Hot-work steels: Many manufacturing operations involve punching, shearing, or forming of metals at high temperatures. Hot-work steels have been developed to withstand the combinations of heat, pressure and abrasion associated with such operations. The main classes of the hot-work steels are: chromium hot-work steels that have chromium and small quantities of molybdenum, tungsten, and vanadium to increase their strength at high temperatures, while maintaining good wear resistance. They are especially well adapted to hot die work of all kinds, particularly dies for the extrusion of aluminum and magnesium, as well as die casting dies, forging dies, mandrels, and hot shears. Tungsten hot-work steels contain tungsten, chromium and vanadium and have been used to make mandrels and extrusion dies for high-temperature applications, such as the extrusion of brass, nickel alloys, and steel, and are also suitable for use in hot-forging dies of rugged design. Molybdenum hot-work steels contain molybdenum, chromium, vanadium, and varying amounts of tungsten and are similar to the tungsten hot-work steels and are identical in their characteristics and applications. Their basic advantage over tungsten hot-work steels is their lower cost.

Cold-work tool steels: Cold work tool steels are the tools steels that are restricted to applications that do not involve prolonged or repeated heating above 400 to 500 °F (205 to 260 °C). The three categories of cold-work steels are: air-hardening steels, high-carbon-high-chromium steels, and oil-hardening steels. The air-hardening steels exhibit minimum distortion and maximum safety in hardening. Manganese, chromium, and molybdenum are the principle alloying elements used to provide this deep hardening. Typical applications of these steels include shear knives, punches, blanking and trimming dies, forming dies, and coining dies. The inherent dimensional stability of these steels make them suitable for gages and precision measuring tools. Their extreme abrasion resistance makes them suitable for brick molds and ceramic molds, and other highly abrasive applications. The high-carbon high-chromium cold-work steels are alloyed with chromium and molybdenum and high amounts of carbon. They are more susceptible to distortion and cracking during hardening. Typical applications of these steels include long-run dies for blanking, forming, thread rolling, and deep drawing; dies for cutting laminations; brick molds; gages; burnishing tools; rolls; and shear and slitter knives. The oil-hardening tools steels are alloyed with one or more of the major alloying elements -

manganese, chromium, tungsten and molybdenum. They are used extensively in dies and punches for blanking, trimming, drawing, flanging, and forming. Oil-hardening tool steels are also used for machinery components, such as cams, bushings, and guides, and for gages, where good dimensional stability and wear resistance properties are needed.

Shock-resisting steels: The principle alloying elements in shock-resisting tool steels are manganese, silicon, molybdenum, chromium, and tungsten in varying combinations. The carbon content is around 0.5% in all of these steels, which produces a combination of high strength, high toughness, and low-to-medium wear resistance. They are used primarily for chisels, rivet sets, punches, driver bits, and other applications requiring high toughness and resistance to shock loading. They are also used in punching and shearing operations, which require some heat resistance.

Low-alloy special purpose steels: These are a group of steels that contain small amounts of chromium, vanadium, nickel, and molybdenum. They are used for machine parts such as arbors, cams, chucks, collets, and other special purpose applications requiring good strength and toughness.

Mold steels: These steels contain nickel and chromium as the main alloying elements. They have very low hardness and low resistance to work hardening in the annealed condition. These factors make it possible to produce a mold impression by cold hubbing. After the impression is formed, the mold is carburized, hardened, and tempered to a high surface hardness. Some of these steels are prehardened and can be machined into intricate dies and molds. This removes the need for heat treatment and avoids distortion.

Quenched and Tempered steels: These tool steels contain carbon as the principle alloying element. Small amounts of chromium (to increase hardenability and wear resistance) and vanadium (to maintain a fine grain structure and enhance toughness) are added to these steels. They have low resistance to softening at elevated temperatures. They are suitable for cold heading, string, coining, and embossing tools; woodworking tools; hard metal-cutting tools, such as taps and reamers; wear-resistant machine tool components; and cutlery.

D.2.3 Stainless Steels

Stainless steels are iron-base alloys containing at least 12% chromium. Few stainless steels contain more than 30% chromium or less than 50% iron. They achieve their stainless characteristics through the formation of an invisible and adherent chromium-rich oxide surface film. This oxide forms and heals itself in the presence of oxygen. Other elements added to improve particular characteristics include nickel, molybdenum, copper, titanium, aluminum, silicon, niobium, nitrogen, sulfur, and selenium. Carbon is normally present in amounts ranging from less than 0.03% to over 1.0% in certain grades. The selection of stainless steels may be based on corrosion resistance, fabrication characteristics, availability, mechanical properties in specific temperature ranges, and product cost. However, corrosion resistance and mechanical properties are usually the most important factors in selecting a grade for a given application.

Wrought stainless steel: Stainless steels have become firmly established as materials: for cooking utensils, fasteners, cutlery, flatware; for decorative architectural hardware; for equipment in chemical plants, dairy and food-processing plants, textile plants, oil and gas industry; for heat exchangers in the power industry; for piping in the nuclear power industry and pulp and paper industry; and the pharmaceutical and transportation industries. Some of these applications involve exposure to elevated or cryogenic temperatures.

Cast stainless steel: Cast stainless steels are either corrosion resistant castings, which are used in aqueous environments below 1200 °F (650 °C), or heat resistant castings, which are suitable for services above 1200 °F (650 °C). Cast stainless steels show fewer stress-corrosion cracking failures compared to equivalent wrought compositions. All cast corrosion resistant steels contain more than 11% chromium and from 1 to 30% nickel. The addition of nickel to stainless steels improves ductility and impact strength. Heat resistant steels are either just iron-chromium steels with 10 to 30% nickel or iron-chromium-nickel steels with more than 13% chromium and more than 7% nickel. They are designed to resist corrosion at elevated temperatures, resist warping, resist cracking, resist thermal fatigue and have high creep strength. Commercial applications of heat resistant stainless steel casting include metal treatment furnaces, gas turbines, aircraft engines, military equipment, oil refinery furnaces, cement mill equipment, petrochemical furnaces, chemical process equipment, power plant equipment, steel mill equipment, turbochargers, and equipment used in manufacturing glass and synthetic rubber.

D.3 Cast Irons

D.3.1 Gray Irons

Cast irons are alloys of iron, carbon, and silicon usually contain 2.5% to 4% carbon, 1% to 3% silicon, and additions of manganese, depending on the desired microstructure. Sulfur and phosphorus are also present in small amounts as residual impurities.

Gray irons are classified based on their tensile strength and exist in grades from 20 to 60 (tensile strengths from 20 kpsi to 60 kpsi). However, in many applications strength is not the crucial factor. For parts such as clutch plates and brake drums, where resistance to heat checking is important, low-strength grades of iron are superior performers. Similarly, in heat shock applications such as ingot or pig molds, a class 25 gray iron shows better performance than a class 60 gray iron. In machine tools and other parts subject to vibration, the better damping capacity of the low-strength irons is often advantageous. In gray cast iron, the following properties increase with an increase from class 20 to class 60:

- All strengths, including strength at elevated temperatures.
- Ability to be machined to a fine finish.
- Modulus of elasticity.
- Wear resistance.

On the other hand, the following properties decrease with increase in tensile strength, so that low-strength irons perform better than the high-strength irons:

- Machinability
- Resistance to thermal shock
- Damping capacity
- Ability to be cast in thin sections

Gray iron is used for many different types of parts in a very wide variety of machines and structures. However gray iron is not recommended where high impact resistance is required. They have considerably lower impact strength than cast carbon steels, ductile iron, or malleable iron. However, they need a minimal impact strength to avoid damage during shipping. The machinability of gray cast irons is superior to most other cast irons of equivalent hardness and all steels. This is because of the flakes of graphite in the iron, which act as chip breakers as well as lubricate the cutting tool. The most demanding applications of gray irons at elevated temperatures are those in which dimensional accuracy is important. To maintain the dimensional stability of gray iron, alloying elements such as copper, molybdenum, chromium, tin, vanadium, and manganese must be added. Creep properties are also improved by adding chromium and molybdenum. Residual stresses may cause problems in cast gray iron parts

D.3.2 Malleable Irons

Malleable iron is a type of cast iron that has most of its carbon in the form of irregular shaped graphite nodules, instead of flakes as in gray iron, or small graphite spherulites as in ductile iron. Malleable iron, like ductile iron, possesses considerable ductility and toughness because of its combination of nodular graphite and a low-carbon matrix. Consequently, malleable iron and ductile iron are suitable for some of the same applications requiring good ductility and toughness, with the choice between them being made on the basis of cost and availability, rather than on properties. Malleable and ductile iron also exhibit high resistance to corrosion, excellent machinability, good magnetic permeability, and low magnetic retention for magnetic clutches and brakes. The good fatigue strength and damping capacity of malleable iron are also useful for long service in highly stressed parts. Small amounts of chromium, boron, copper, nickel and molybdenum are present in malleable iron to enhance its properties.

Applications

Malleable iron is preferred over ductile iron in the following applications:

- Thin-section castings.
- Parts that are to be pierced, coined, or cold formed.
- Parts that require maximum machinability.
- Parts that must retain good impact resistance at low temperatures.
- Parts requiring wear resistance (martensitic malleable iron only).

Ductile iron is more advantageous in cases where thick sections are required, and when low solidification shrinkage is needed.

D.3.3 Ductile (Nodular) Irons

Ductile cast iron, previously known as nodular or spheroidal-graphite cast iron, is cast iron in which the graphite is present as tiny spheres. Because of the additives introduced in the molten iron before casting, the graphite grows as spheres, rather than as flakes as in gray iron.

The relative high strength and toughness of ductile iron gives it an advantage over either gray iron or malleable iron in many structural applications. Ductile iron does not need heat treatment and can therefore compete with malleable iron even though it requires special treatment and inoculation process before casting. Ductile iron castings are used for many structural applications, particularly those requiring strength and toughness combined with good machinability and low cost. Properties unique to ductile iron include the ease of heat treating, because the carbon in the matrix can be re-dissolved to any desired level to control the hardness and strength. Ductile iron can be tempered to exhibit high tensile strength, high fatigue strength, high toughness, and excellent wear resistance. Due to the lower density of ductile iron, it weighs 10% less than steel for the same section size. The graphite content provides damping for quiet running gears. The low coefficient of friction produces more efficient gear boxes. Ductile iron has less tendency to gear seizures from the loss of lubricant. Ductile iron castings are consistent in dimensions and weight because there is no distortion or growth due to heat treatment. Ductile iron can be rolled or spun into a desired shape or coined to an exact dimension.

Applications

The automotive and agricultural industries are the major users of ductile iron castings. Because of economic advantages and high reliability, ductile iron is used for such critical automotive parts as crankshafts, front wheel spindle supports, complex shapes of steering knuckles, disk brake calipers, engine connecting rods, idler arms, wheel hubs, truck axles, suspension system parts, power transmission yokes, high-temperature applications for turbo housings and manifolds, and high-security valves for many applications.

D.3.4 Alloy Cast Iron

Alloy cast irons are considered to be those casting alloys based on the iron-carbon-silicon system that contain one or more alloying elements intentionally added to enhance one or more useful properties. Small amounts of alloying elements such as chromium, nickel or molybdenum are added to achieve high strength and hardness. Otherwise, alloying elements are used almost exclusively to enhance resistance to abrasive wear or chemical corrosion or to extend the service life at elevated temperatures. The main classes of alloy cast irons are: abrasion resistant white irons, corrosion resistant irons, heat resistant (gray or ductile) irons.

White cast irons are so named because of their white fracture surface. White cast irons are usually very hard, which is the single property most responsible for their excellent resistance to abrasive wear. The white irons are alloyed with chromium to increase their hardness and wear resistance. The silicon in white iron is kept to a minimum, since silicon has a negative effect on the hardenability. Small amounts of nickel, molybdenum, manganese and copper also help to increase the hardness of white irons. High amounts of carbon are essential for high hardness and maximum wear resistance in unalloyed white irons.

Corrosion resistant irons derive their resistance to chemical attack chiefly from their high alloy content. The corrosion resistance of cast irons is enhanced by the addition of appreciable amounts of nickel, chromium, and copper, singly, or in combination, or silicon in excess of about 3%. Silicon in excess of 3% promotes the formation of a strong protective surface film under oxidizing conditions, such as exposure to oxidizing acids. Silicon also increases the wear resistance of cast irons. High silicon irons are the most common of the corrosion resistant alloy cast irons. They have poor mechanical properties and poor shock resistance, both mechanical and thermal. They are widely used for drain pipes in chemical plants, labs, hospitals and schools. They are used in tubes, towers and fitting in the explosives and fertilizers industries. They are also used in pumps, valves, mixing nozzles, tank outlets and steam jets used for handling highly corrosive acids. The addition of nickel improves the resistance of cast irons to reducing acids and caustic alkalis. The high nickel irons are very tough and have excellent machinability and ductility. They provide satisfactory corrosion resistance at elevated temperatures up to 1300 to 1500 °F (705 to 815 °C). These irons are used for annealing pots; lead, zinc, or aluminum melting pots; conveyor links; and other parts exposed to corrosion at high temperatures. They are specifically used at corrosive environments at temperatures that are higher than can be handled by the nickel alloyed irons.

Heat resistant irons combine resistance to high temperature oxidation and scaling with resistance to softening or microstructural degradation. The heat resistant cast irons are basically alloys of iron, carbon and silicon having high-temperature properties markedly improved by the addition of alloying elements such as chromium, nickel, molybdenum, aluminum, and silicon in excess of 3%. Silicon and chromium increase the resistance to heavy scaling by forming a light surface oxide that is impervious to oxidizing atmospheres. Nickel and molybdenum increase the strength and toughness at elevated temperatures. Aluminum helps reduce growth and scaling at high temperatures

D.4 Special Purpose Alloys

D.4.1 Low Expansion Alloys

Low-expansion alloys include various iron-nickel alloys and several alloys of iron combined with nickel-chromium, nickel-cobalt, or cobalt-chromium. Some of the trade names of the low-expansion alloys used, and their compositions are:

- *Invar*,(Imphy, S.A) which is a 64% iron - 36% nickel alloy with the lowest thermal coefficient of iron-nickel alloys.

- *Kovar*,(Carpenter Technology Corporation) which is a 54% iron - 29% nickel - 17% cobalt alloy with coefficients of expansion closely matching those of standard types of hard glass.
- *Elinvar*, (Imphy, S.A) which is a 52% iron - 36% nickel - 12% chromium alloy with a zero thermoelastic coefficient; that is, an invariable modulus of elasticity over a wide temperature range.
- *Super Invar*,(Imphy, S.A) which is a 63% iron, 32% nickel, 5% cobalt alloy with an expansion coefficient smaller than Invar, but over a narrower temperature range.

Iron-nickel alloys: Alloys of iron and nickel have coefficients of linear expansion ranging from a small negative value (-0.5×10^{-6} per °C) to a large positive value (20×10^{-6} per °C). In the range of 30% to 60% nickel, it is possible to select alloys with appropriate expansion characteristics. The alloy containing 36% nickel (with small quantities of manganese, silicon, and carbon amounting to a total of less that 1%) has a coefficient of expansion so low that its length is almost invariable for ordinary changes in temperature. This alloy is Invar. Iron-nickel alloys having higher contents of nickel than Invar retain to some extent the expansion characteristics of Invar. Alloys that contain less than 36% of nickel have much higher coefficients of expansion that alloys containing 36% or more nickel. There are applications where alloys with amounts of nickel above or below 36% are useful. The alloy containing 39% of nickel has a coefficient of expansion corresponding to that of low-expansion glasses. Alloys containing 30% to 34% nickel are temperature-compensator alloys, which exhibit linear changes in magnetic characteristics with temperature change. They are used as compensating shunts in metering devices and speedometers. Alloys having around 42% nickel are used in semiconductor packaging components, thermostat bimetals, incandescent light bulb glass seal leads, and seal beam lamps. Dumet wire is an alloy containing 42% nickel. It is clad with copper to provide improved electrical conductivity and to prevent gassing at the seal. It can replace platinum as the seal-in wire in incandescent lamps and vacuum tubes. The alloys containing 43% to 47% nickel are commonly used for glass seals, grommets, and filament supports.

Iron-nickel-chromium alloys: Elinvar is a low expansion iron-nickel-chromium alloy with a thermoelastic coefficient of zero over a wide temperature range. It is more practical than the straight iron-nickel alloys with a zero thermoelastic coefficient, because its thermoelastic coefficient is less susceptible to variations in nickel content expected in commercial melting. Elinvar is used for articles such as hairsprings and balance wheels for clocks and watches and for tuning forks used in radio synchronization. Particularly beneficial where an invariable modulus of elasticity is required, it has further advantage of being comparatively rust proof. Other iron-nickel-chromium alloys with 40 to 48% nickel and 2 to 8% chromium are useful as glass-sealing alloys because the chromium promotes glass-to-metal bonding as a result of its oxide forming characteristics.

Iron-nickel-cobalt alloys: Replacement of some of the nickel by cobalt in an alloy of the Invar composition lowers the thermal expansion coefficient and makes the alloy's expansion characteristics less susceptible to variations in heat treatment. These iron-nickel-cobalt alloys (known as Super-Invar), however, have a more restrictive temperature range of useful application.

Iron-cobalt-chromium alloys: An alloy containing 36.5% to 37% iron, 53% to 54.5% cobalt, and 9% to 10% chromium has an exceedingly low, and at times, negative coefficient of expansion over the range from 32 to 212 °F (0 to 100 °C). This alloy has good corrosion resistance compared to low-expansion alloys without chromium. Consequently, it has been referred to as stainless Invar.

Hardenable low expansion alloys: Alloys that have low coefficients of expansion, and alloys with constant modulus of elasticity, can be made age hardenable by adding titanium. In the low-expansion alloys, the nickel content must be increased if titanium is added.

High-strength, controlled expansion alloys: There is a family of iron-nickel-cobalt alloys strengthened by the addition of niobium and titanium that show the combination of exceptional strength and low coefficient of expansion to make this family useful for applications requiring close operating tolerances over a range of temperatures. Several components for gas turbine engines are produced from these alloys. Some of these alloys are sold under the trade name Incoloy(Inco Alloys International, Inc.).

Applications

Low expansion alloys are used as rods and tapes for geodetic surveying; compensating pendulums and balance wheels for clocks and watches; moving parts that require control of expansion - such as pistons for some internal combustion engines; bimetal strips;, glass-to-metal seals; thermoelastic strips, vessel and piping for storage and transportation of liquefied natural gas; superconducting systems in power transmissions;, integrated-circuit lead frames; components for radios and other electronic devices; and structural components in optical and laser measuring systems. They are also used along with high-expansion alloys to produce movements in thermoswitches and other temperature-regulating devices.

D.4.2 Permanent Magnet Materials

Permanent magnet is the term used to describe solid materials that have sufficiently high resistance to demagnetizing fields and sufficiently high magnetic flux output to provide useful and stable magnetic fields. Permanent magnets are normally used in a single magnetic state. This implies insensitivity to temperature effects, mechanical shock, and demagnetizing fields. Permanent magnet materials include a variety of alloys, intermetallics, and ceramics. Commonly included are certain steels, Alnico(PMA), Cunife, iron-cobalt alloys containing vanadium, or molybdenum, platinum-cobalt, hard ferrites, and rare-earth alloys. Each type of magnet material posses unique magnetic and mechanical properties, corrosion resistance, temperature sensitivity, fabrication limitations, and cost. These factors provide designers with a wide range of options in designing magnetic parts. Permanent magnet materials are developed for their chief magnetic characteristics: high induction, high resistance to demagnetization, and maximum energy content. Maximum energy content is most important because permanent magnets are used primarily to produce a magnetic flux field.

Magnet steels: Until about 1930, all the commercial permanent magnet materials were quench hardened steels. Today these steels are considered obsolete.

Magnet alloys: These are a series of alloys of iron and cobalt plus molybdenum or tungsten. These alloys became known as Remalloy, Cunife, Cunico, and Vicalloy(Telcon). With the exception of Cunife, these alloys are now obsolete. Commercial Cunife contains approximately 20% iron, 20% nickel, and 60% copper. The material is extremely anisotropic, with the superior magnetic properties in the direction of rolling, a factor that must be considered in magnet design. The mechanical softness of this alloy permits easy cold reduction and working, thus leading to many applications in the form of wire or tape.

Alnico alloys: Alnico alloys are one of the major classes of permanent magnet materials. The Alnico vary widely in composition and in preparation, to give a broad spectrum of properties, costs, and workability. Alnico alloys are brittle and hard and can be machined only by surface grinding, electrical discharge machining, or electrochemical milling. They resist atmospheric corrosion well up to 930 °F (500 °C). Magnetic properties are negligibly affected by vibration or shock. Generally, Alnico is superior to other permanent magnet materials in resisting temperature effects on magnetic performance.

Platinum-cobalt alloys: Although platinum-cobalt magnets are expensive, they are used in certain applications. Platinum-cobalt is isotropic, ductile, easily machined, resistant to corrosion at high temperatures, and has magnetic properties superior to all except the rare earth/cobalt alloys. Best magnetic properties are obtained at an atomic ratio of 50% platinum and 50% cobalt.

Cobalt and rare-earth alloys: Permanent magnet materials based on combinations of cobalt and the lighter rare-earth lanthanide) metals are the materials of choice for most small, high-performance devices operating between 345 to 660 °F (175 to 350 °C). These materials are manufactured by powder metallurgy methods, and have low temperature coefficients that can be altered by additions of a heavy rare-earth, such as gadolinium or holmium.

Hard ferrites: Also known as ceramic permanent magnet materials, hard ferrites are predominantly complex oxides. Ceramic permanent magnets have high electrical resistivities and are poor conductors of heat. They are not affected by high temperatures or by atmospheric corrosion, but their magnetic properties are more temperature dependent than other permanent magnet alloys.

Iron-chromium-cobalt alloys: Anisotropic iron-chromium-cobalt permanent magnet alloys have magnetic properties that are comparable to the Alnico.

Neodymium-iron-boron alloys: These alloys have become the material of choice for a wide range of permanent magnet applications. They are processed by powder metallurgy or by the consolidation of rapidly solidified materials.

D.4.3 Electrical Resistance Alloys

Electrical resistance alloys include those types used in instruments and control equipment, heating elements, and devices that convert heat generated into mechanical energy. They are classified as resistance alloys, thermostat metals and heating alloys.

Resistance Alloys

The primary requirements for resistance alloys are uniform resistivity, stable resistance (no time-dependent aging effects), reproducible temperature coefficients of resistance, and low thermoelectric potential versus copper. Properties of secondary importance are coefficient of expansion, mechanical strength, ductility, corrosion resistance, and ability to be joined to other metals by soldering, brazing, or welding. Availability and cost are also factors. Resistance alloys must be ductile enough so that they can be drawn into wire as fine as 0.004 inches (0.01 mm) in diameter or rolled into narrow ribbon from 0.016 to 2 inches (0.4 to 50 mm) wide and from 0.001 to 0.15 inches (0.023 to 3.8 mm) thick. Alloys must be strong enough to withstand fabrication operations, and it must have consistently reproducible properties. The types of resistance alloys that are used commercially are:

Copper-nickel resistance alloys are generally referred to as radio alloys. These alloys have very low resistivities and moderate temperature coefficient of resistance. Resistivity of the radio alloys increases, and the temperature coefficient of resistance decreases, as the nickel content increases. All radio alloys can be readily soldered or brazed. Because of their high copper contents, radio alloys have low resistance to oxidation and thus are restricted to applications involving low operating temperatures. They are chiefly used for resistors that carry relatively high currents.

Copper-manganese-nickel resistance alloys are generally referred to as manganins. These alloys have been adopted almost universally for precision resistors, slide wires and other resistive components with values of 1kΩ or less, and are also used for components with values up to 100kΩ. All manganins are moderate in resistivity (from 230 t0 290 mΩ/ft [380 to 480 nΩ/m]) and low in temperature coefficient of resistance (less than ±15 ppm/°C). The resistance values of manganins change no more than 1 ppm per year when the material is properly heat treated and protected.

Constantan, which like manganin, has become a generic term for a series of alloys that have moderate resistivities and low temperature coefficients of resistance. Nominally constantan is 55% copper - 45% nickel alloys, but specific compositions vary from 50% copper - 50% nickel to about 65% copper - 35% nickel. The temperature coefficient of conventional constantan can be held to within ±20 ppm/°C of ambient temperature. Constantan is considerably more resistant to corrosion than manganins. Use of constantan as electrical resistance alloys is restricted largely to ac circuits, because thermoelectric potential versus copper is quite high for these materials (about 40μV/°C at room temperature).

Nickel-chromium-aluminum resistance alloys contain small amount of metals like copper, manganese, or iron. These alloys have resistivities about 2.5 to 3.5 times that of manganin. Nickel-chromium-aluminum resistance alloys have been adopted almost universally for the construction of wire-wound precision resistors having resistance values about 100kΩ, and are also used for resistors with values as low as about 100Ω. The temperature coefficient of resistance of these alloys are vastly superior to those of manganin and constantan, being less than ±20 ppm/°C between -67 and 220 °F (-55 to 105 °C).

Thermostat Metals

A thermostat metal is a composite material, usually in the form of a strip or a sheet, that consists of two or more materials bonded together, one of which may be a non-metal. Because the materials bonded together to form the composite differ in thermal expansion, the curvature of the composite is altered by changes in temperature; this is the fundamental characteristic of any thermostat material. A thermostat material is, therefore a system that transforms heat into mechanical energy for control, indicating, or monitoring purposes. In applications such as circuit breakers, thermal relays, motor overload protectors, and flashers, the change in temperature necessary for the operation of the element is produced by the passage of current through the element itself. This means that the material should have a high electrical resistivity. Most thermostats are nickel-iron, nickel-chromium-iron, chromium-iron, high-copper, or high-manganese alloys. They are available in strips or sheets in thickness ranging from 0.005 to 0.125 inches. (0.13 to 3.2 mm). They are easily formed into required shapes. They are also available for various operating ranges between -300 and 1000 °F (-185 and 540 °C).

Heating Alloys

Resistance heating alloys are used in many varied applications, from small household appliances to large industrial process heating systems and furnaces. The primary requirements of materials used in heating elements are high melting point, high electrical resistivity, reproducible temperature coefficient of resistance, good oxidation resistance, absence of volatile components, and resistance to contamination. Other desirable properties are good elevated-temperature creep strength, high emissivity, low thermal expansion, and low modulus (both of which help minimize thermal fatigue), good resistance to thermal shock, and good strength and ductility at fabrication temperatures. There are four main groups of resistance heating materials:

Nickel-chromium and nickel-chromium-iron alloys serve the greatest number of applications. The ductile wrought alloys in this group have properties that enable them to be used at both low and high temperatures in a wide variety of environments.

Iron-chromium-aluminum alloys, which are also ductile alloys, play an important role in heaters for the higher temperature ranges, and are constructed to provide more effective mechanical support for the element. They have excellent resistance to oxidation at elevated temperatures due to the formation of an aluminum oxide coating on the surface. They have low tensile strengths. Powder processing methods used to produce these alloys can help improve mechanical properties.

The pure metals, which are basically molybdenum, platinum, tantalum and tungsten, have much higher melting points, low resistivities, and very high temperature coefficients of resistance. Molybdenum and tantalum have high tensile strengths, even at high temperatures. All of them, except platinum, are readily oxidized and are restricted to use in non-oxidizing environments. They are valuable for a limited range of application, primarily for service above 2500 °F (1370 °C). The cost of platinum prohibits its use except in small, special furnaces.

The nonmetallic heating-element materials are used at still higher temperatures, and include silicon carbide, molybdenum disilicide, and graphite. Graphite and silicon carbide have high resistivity and negative temperature coefficient of resistance. Molybdenum silicide elements have low resistivity and very high positive temperature coefficients of resistance. Silicon carbide can be used in oxidizing atmospheres at temperatures up to 3000 °F (1650 °C). Graphites have poor oxidation resistance and should not be used at temperatures above 750 °F (400 °C). Molybdenum disilicides are effective up to maximum temperatures of 3100 to 3450 °F (1700 to 1900 °C).

Molybdenum disilicide heating elements are gaining increased acceptance for use in industrial and laboratory furnaces. Among their desirable properties are excellent oxidation resistance, long life, constant electrical resistance, self-healing ability, and resistance to thermal shock. Nonmetallic heating elements are considerably more fragile than the metal heating element alloys. All of them have low tensile strengths. However, because of their high resistivity, silicon carbide elements are made with large cross sections to reduce resistance and as a result, can withstand high mechanical loads.

PART II NONFERROUS ALLOYS

D.5 Light Alloys

D.5.1 Zinc Alloys

Zinc alloys have low melting points, require relatively low heat input, do not require fluxing or protective atmospheres, and are non-polluting; the last is a particularly important advantage. Because of their high fluidity, zinc alloys can be cast in much thinner walls than other die casting alloys, and they can be die cast to tighter dimensional tolerances. Zinc alloys allow the use of very low draft angles. Zinc alloy castings can be conveniently joined by soldering (using new zinc base solders since cadmium, tin or lead base solders are not longer suitable), brazing, or by certain welding techniques using zinc-base fillers. Adhesive bonding or mechanical fasteners are also excellent methods for joining castings.

In addition to their excellent physical and mechanical properties, zinc alloys offer:

- Good corrosion resistance.
- Excellent vibration and sound damping properties that increase exponentially with temperature.
- Excellent bearing and wear properties.
- Spark resistance (with the exception of the high aluminum content alloys).

Zinc and its alloys are used extensively in both gravity and pressure die castings. When used as general casting alloys, zinc alloys can be cast using such processes as high-pressure die casting, low-pressure die casting, sand casting, permanent mold casting (using iron, graphite, or plastic molds), spin casting (using silicone rubber molds), investment casting, continuous or semi continuous casting, and centrifugal casting.

Zinc in either pure form or with small amounts of alloying additions is used in three main types of wrought products: flat-rolled products, wire-drawn products, and extruded and forged products. Wrought zinc is readily machined, joined and finished. Super plastic zinc, which contains 21 to 23% aluminum and a small amount of copper (0.4 to 0.6%) can be easily formed into complex shapes and displays the characteristics of plastic or molten glass at temperature of 250 to 270 °C (480 to 520 °F).

Rolled zinc can be formed into many different shapes by bending, spinning, deep drawing, roll forming, coining, and impact extrusion. Joining is easily achieved by soldering and resistance welding. When alloyed with copper and titanium, zinc sheet has high creep resistance and can be used in functional applications, including architectural applications such as in roofing and siding. The manufacture of zinc alloy wire is normally continuous and follows casting, rolling, and drawing operations. Zinc alloy wire is widely used in thermal spraying, or metallizing, where the wire is melted and sprayed onto a substrate using a special gun. This process is used primarily for the corrosion protection of steel. In addition to pure zinc, zinc alloys containing 15% aluminum are used in thermal spraying applications because the zinc-aluminum alloy provides increased corrosion protection. Zinc alloy wire is also used in nail and screw production and in zinc-base solders.

There are two *zinc forging alloys* that are currently in commercial use. One has a zinc-aluminum base and has high impact strength at low temperatures. The other alloy contains copper and titanium and is a more general purpose alloy, which has better creep strength. Both alloys have excellent machining, joining, and finishing characteristics, although machining of the titanium-containing alloy is best performed with carbide-tipped tooling. Zinc alloys are generally capable of being extruded but require higher pressures and lower speeds than other nonferrous metals. Extrusion offers near-net-shape capability with minimal or no machining.

D.5.2 Aluminum Alloys

The properties of aluminum that make this metal and its alloys attractive for a wide variety of uses are appearance, lightweight, fabricability, physical properties, mechanical properties, and corrosion resistance. Aluminum surfaces can be highly reflective and used in a number of decorative and functional uses. Its excellent electrical and thermal conductivity are advantageous in heat exchangers, evaporators, electrically heated appliances, and automotive cylinder heads and radiators. Its non-ferromagnetic property finds use in the electrical and electronics industry. It is non-toxic and is therefore used in containers for foods and beverages. It is extremely lightweight and finds use in the aerospace industry in aircraft frames, missile bodies, satellite components, etc. Some aluminum alloys exceed the structural strength of steel. Aluminum and its alloys are also used in a number of domestic applications like mirror frames, utensils, food trays, portable equipment like vacuum cleaners, electric irons and similar appliances, furniture etc. Aluminum is also used as a foil to package many materials including food items.

Aluminum wrought alloys are classified as follows:

1xxx Series: Aluminum of 99% or higher purity has many applications, especially in the electrical and chemical industries. These grades of aluminum have excellent corrosion resistance, high thermal and electrical conductivities, low mechanical properties, and excellent workability. Typical uses include chemical equipment, reflectors, heat exchangers, electrical conductors and capacitors, packaging foil, architectural applications, and decorative trim.

2xxx Series: Copper is the principle alloying element with some amounts of magnesium also added. When heat treated, these alloys have mechanical properties comparable to those of low-carbon steel. They do not have as good corrosion resistance as the other aluminum alloys, and are clad with high purity aluminum or with the *6xxx* series to obtain excellent corrosion resistance characteristics. These alloys are well suited for parts and structures requiring high strength to weight ratios and are commonly used to make truck and aircraft wheels, truck suspension parts, aircraft fuselage and wing skins, and structural parts and those parts requiring good strength up to 300 °F (150 °C). These alloys have limited weldability, but superior machinability when compared to other aluminum alloys.

3*xxx* Series: Manganese is the major alloying element in this series. These alloys are non-heat treatable. Alloys of these series are used in moderate-strength applications requiring good workability like beverage cans, cooking utensils, heat exchangers, storage tanks, awnings, furniture, highway sings, roofing, siding, and other architectural applications.

4*xxx* Series: Silicon is the major alloying element in this series. Silicon lowers the melting point of the alloy without increasing the brittleness. For this reason, the alloys of this series are used in welding wire and as brazing alloys for joining aluminum. Some alloys in this series have a low coefficient of thermal expansion and high wear resistance, and is well suited for the production of forged engine pistons.

5*xxx* Series: Magnesium is the major alloying element in this series. When it is used as the only alloying element or with manganese, the resulting alloy is a moderate-to-high-strength, work-hardenable alloy. Alloys of this series possess good welding characteristics and good resistance to corrosion in marine atmospheres. Uses include architectural, ornamental, and decorative trim; cans and can ends; household appliances; streetlight standards; boats and ships, cryogenic tanks; crane parts; and automotive structures.

6*xxx* Series: These alloys contain silicon and magnesium in the right proportion to form magnesium silicide. Although not as strong as the 2*xxx* or 7*xxx* series, they have good formability, weldability, machinability, and corrosion resistance, with medium strength. They are used in architectural applications, bicycle frames, transportation equipment, bridge railings, and welded structures.

7xxx Series: Zinc is the major alloying element in this series. With small percentages of magnesium, heat treatable alloys of moderate to very high strength can be obtained. They are used in aircraft structures, mobile equipment, and other highly stressed parts.

In addition to these series there are aluminum-lithium alloys, which have been developed primarily to reduce the weight of aircraft and aerospace structures. More recently they have been investigated for use in cryogenic applications because of their low density, high specific modulus and excellent fatigue and cryogenic toughness properties. They have not directly replaced conventional aerospace aluminum alloys because of their reduced ductility and fracture toughness, their accelerated fatigue, and their high explosion potential with water.

Aluminum cast alloys are classified as follows:

2xx.x Series: Copper is the major alloying element with small amounts of magnesium. Though excellent high-strength and high-ductility casting have been obtained with these alloys, they are not very easily cast. Of late, only high copper content alloys are used. They find use in applications that require high-temperature strength and good wear resistance as in aircraft cylinder heads and in automotive (diesel) pistons and cylinder blocks.

3xx.x Series: These alloys contain both silicon and copper as alloying elements. The copper increases the strength while the silicon increases the castablility, wear resistance and thermal expansion. Automotive engine blocks and pistons are major uses of these alloys. They are also used in jet engine compressor cases, tank engine cooling fans, and high speed rotation parts such as impellers.

4*xx.x* Series: These alloys contain silicon as the major alloying element. They are used in applications requiring good castability and good corrosion resistance. The alloys of this series that have excellent tensile strengths are used in the automobile and aerospace industries.

5*xx.x* Series: These alloys contain magnesium as the primary alloying element. They have moderate-to-high strength and toughness properties. High corrosion resistance, especially to sea water and marine atmospheres, which is the primary advantage of these alloys. They are used in marine applications including hatch covers, ladders, bulkheads, lifesaving equipment, canoes, oars, paddles, sonobuoys, rowboats, etc. They also find use in architectural and other decorative or building needs.

7*xx.x* Series: Zinc is the major alloying element with small amounts of magnesium. They have moderate to good strength characteristics and with annealing they have good dimensional stability. They also have good machinability, though their castability is poor.

8*xx.x* Series: Tin is the major alloying element in these alloys and small amounts of copper and nickel are used for improving the strength. These alloys are used for cast bearings because of the excellent lubricity imparted by tin. They are used for bearing applications where load-carrying capacity, fatigue strength, and resistance to corrosion by the lubrication oils are important criteria. They are also used in engine connecting rods.

D.5.3 Magnesium Alloys

Pressure die casting alloys

There are three systems of magnesium alloys used commercially for high pressure die castings: magnesium-aluminum-zinc-manganese (AZ), magnesium-aluminum-manganese (AM), and magnesium-aluminum-silicon-manganese (AS). An AZ type alloy is the most commonly used die casting alloy. The AZ alloys exhibit good mechanical and physical properties in combination with excellent castability and saltwater corrosion resistance. The AM series of alloys are used in applications requiring greater ductility than can be provided by the AZ series. The tensile and yield strengths of the AM series are comparable to the AZ series. These alloys are used in the production of die cast automobile wheels and in some archery and other sports equipment. The AM series also exhibits excellent corrosion resistance. The AS series of alloys are used when excellent creep strength is required. It also has good elongation, yield strength, and tensile strength. It is used in crankcases of air cooled automotive engines.

<u>Sand and permanent mold casting alloys</u>

The magnesium sand and permanent mold casting alloys that contain aluminum as the primary alloying ingredient exhibit good castability, good ductility, and moderately high yield strength at temperatures up to approximately 250 °F (120 °C). Elimination of impurities in these alloys can also lead to excellent salt water corrosion resistance. In any of the magnesium-aluminum-zinc alloys, an increase in the aluminum content raises the yield strength, but reduces the ductility from comparable heat treatment.

Magnesium alloys that contain high levels of zinc develop the highest yield strengths of the casting alloys and can be cast into complicated shapes. They are, however, costly, and used only where exceptional good yield strengths are required. They are intended primarily for use at room temperature. Addition of thorium to these alloys helps overcome their susceptibility to microporosity, hot cracking and low weldability. Manganese is effective in improving the corrosion resistance of magnesium alloys that contain aluminum and zinc. Alloys that do not contain aluminum or zinc, but contain yttrium, also exhibit good corrosion resistance.

The magnesium-zirconium alloys are used at temperatures between 350 and 500 °F (175 and 260 °C). Because their high-temperature strengths exceed those of the magnesium-aluminum-zinc alloys, thinner walls can be used, and a savings in weight is possible. Magnesium-thorium-zirconium alloys can also be used at high temperatures; however, these alloys cannot be used for thin sections.

Applications

Magnesium and magnesium alloys are used in a wide variety of structural and non-structural applications. Structural applications include automotive, industrial, materials-handling, commercial and aerospace equipment. The automotive applications include clutch and brake pedal support brackets, steering column lock housings, and manual transmission housings. In industrial machinery, such as textile and printing machines, magnesium alloys are used for parts that operate at high speeds and thus must be lightweight to minimize inertial forces. Materials-handling equipment includes dock boards, grain shovels, and gravity conveyors. Commercial applications include hand held tools, luggage, computer housings, and ladders. Magnesium alloys are valuable for aerospace applications because they are light weight and exhibit good strength and stiffness at both room and elevated temperatures.

Magnesium is also employed in various non-structural applications. It is used as an alloying element in alloys of aluminum, zinc, lead, and other nonferrous metals. It is used as an oxygen scavenger and desulfurizer in the manufacture of nickel and copper alloys; as a desulfurizer in the iron and steel industry, and as a reducing agent in the production of beryllium, titanium, zirconium, hafnium, and uranium. The relative position of magnesium in the electromotive series allows it to be used for cathodic protection of other metals from corrosion and in the construction of dry-cell, sea water, and reserve-cell batteries. Magnesium and magnesium alloys are used to improve the toughness and ductility of cast iron. Magnesium is also used in photoengraving due to its light weight and its rapid but controllable response to etching.

D.5.4 Titanium Alloys

Titanium and its alloys have become indispensable in a number of applications in the aircraft industry, and are still finding applications where corrosion resistance is important, such as in the marine and biomedical industries. However, aerospace still account for the largest share of titanium alloy use. Commercially pure titanium is more commonly used than titanium alloys for corrosion applications, especially when high strength is not a requirement.

Titanium alloys are classified as either alpha alloys, near alpha alloys or alpha-beta alloys and beta alloys, depending on the crystal structure of the titanium in the alloy. Alpha alloys are less corrosion resistant, but higher in strength than pure titanium. The principal alloying element is aluminum with small amounts of tin. Near alpha alloys are very similar to titanium alloys in their properties, but have small quantities of beta stabilizers like vanadium, molybdenum, zirconium and niobium. Again aluminum is the principal alloying element. The alpha-beta alloys contain 4-8% of either vanadium, niobium or molybdenum. They have good ductility and formability, higher corrosion resistance and higher strength and fatigue properties than the other titanium alloys. The beta alloys contain 8-15% of vanadium or molybdenum. These alloys have lower strengths than the alpha-beta alloys, but have good ductility, superior creep properties and higher fracture-toughness value.

The principal alloying elements of titanium have the following effects:

- *Aluminum*, which increases tensile strength, creep strength, and the elastic modulus. The amount of aluminum in titanium is typically below 7%, since further increase in aluminum causes embrittlement of the alloy.
- *Tin*, which is used along with aluminum to achieve higher strength without embrittlement. Alloys with tin in them are denser and have a lower elastic modulus that those alloys with aluminum alone; however, they have a better combination of strength and temperature capability.
- *Zirconium*, which increases the strength of titanium at low and intermediate temperatures. Zirconium amounts are kept below 5-6%, since greater quantities can reduce the ductility and creep strength of titanium.
- *Niobium*, which improves oxidation resistance at high temperatures.
- *Iron*: which when used in small quantities can improve creep strength.

Applications

Chemical and petrochemical processing equipment including vessels, pumps, fractional columns, and storage tanks

Marine engineering products including propeller and rudder shafts, thrusters pumps, lifeboat parts, deep sea pressure hulls, and submarine components

Energy production and storage equipment including plate-type heat exchangers, condensers, piping and tubing using sea water for cooling, steam-turbine blades, and generator retaining rings all use titanium and its alloys to a great extent.

Recently, titanium alloys are used in flue gas desulfurization units and as canisters to contain low-level radioactive waste, such as spent fuel from nuclear power plants. Titanium and its alloys are also used in biomedical applications including implantable pumps and components for artificial hearts, hip and knee implants, because of their resistance to corrosion by body fluids.

Titanium and its alloys are now being investigated for use in valve systems and suspension springs in the automobile industry due to their high specific strength. Racing automobile have made extensive use of titanium alloys for engine parts, drive systems, and suspension components for some years. Titanium has also been used as a building material for some time. Although costlier than steel, titanium is considered cost effective in structures erected in the tropics and other areas where buildings are exposed to strong, warm sea winds. Titanium is also being used in special applications that exploit unique properties such as superconductivity (titanium alloyed with niobium) and the shape-memory effect (titanium alloyed with nickel).

Manufacturing Methods

Titanium alloys are forged into a variety of shapes. However, titanium alloys are considerably more difficult to forge than aluminum alloys and alloy steels, particularly with conventional forging techniques. Most titanium forgings are produced to less highly complex configurations than are aluminum alloy forgings. Titanium alloy forgings are also heat-treated after forging to relieve built in stresses, as well as to modify the microstructure of the alloy to obtain specific mechanical properties. The dies used in the conventional forging of titanium alloys, unlike some other materials, are heated to facilitate the forging process and to reduce metal temperature loss during the forging process. In addition, cooling techniques need to be used on the dies to prevent damage due to heat transfer that occurs from the metal to the die.

Titanium alloys are extruded to obtain rod like shapes and seamless pipe products. Titanium and titanium alloy sheets and plates are obtained by cold rolling, which increases tensile and yield strengths and causes a slight drop in the ductility. Since titanium is costly, it is preferred to use near-net-shape technologies to process titanium and its alloys. Precision casting is by far the most widely used net-shape technology to process titanium and its alloys. The term casting is associated with properties generally inferior to wrought products. This is not true with titanium cast parts. They are generally comparable to wrought products in all respects and often superior in properties associated with crack propagation and creep resistance. Cast products that undergo hot isostatic pressing have no subsurface porosity. This promotes a favorable microstructure and improves mechanical properties. Investment casting is the process that allowed titanium to become indispensable in the aircraft industry. Ceramic slurries have been developed in the investment casting process to minimize the reaction with the extremely reactive molten titanium.

Powder metallurgy has also been used as a near-net-shape manufacturing process to produce a number of aerospace components. These techniques are being used to produce titanium alloys with novel compositions that would be impossible to achieve through conventional processing. Titanium-base intermetallics have better oxidation resistance, lower density, improved creep resistance, and higher modulus than conventional titanium alloys.

D.6 Heavy Alloys

D.6.1 Copper Alloys

Copper and its alloys are widely used because of their excellent electrical and thermal conductivities, outstanding resistance to corrosion, ease of fabrication, and good strength and fatigue resistance. They are generally non-magnetic and non-sparking, and can be soldered, welded and brazed. For decorative parts, different colors are available, and they can be polished and buffed to any desired texture and luster. They can also be plated to obtain a variety of finishes. Copper and its alloys are not heat-treatable and cannot be hardened by application of heat following a quench. Hardness is produced by cold working, and softening is produced by heating above the recrystallization temperature.

Pure copper: Pure copper is alloyed with many other elements to produce minor changes in properties. Chromium, zirconium, cadmium, and tin are added to improve the strength. Silver is added in small quantities to obtain improved heat resistance. Total alloy additions in pure copper are usually less than 1%.

Brass: Plain brasses are alloys of copper and zinc. There are different kinds of brasses depending upon the zinc content. Red brass contains about 15% zinc. In the cast form, red brass is usually an alloy of 85% copper, 5% zinc, 5% tin, and 5% lead. Red brasses are used for plumbing goods, flanges, feed pumps, meter casings and parts, hydraulic and steam valves, valve disks and seats, impellers, injectors, memorial markers, plaques, statuary, and similar products. Yellow brass contain around 30% zinc. They are frequently alloyed with several percent of lead to improve the machinability. They are used for plumbing goods and accessories, low-pressure valves, air and gas fittings, general hardware, and ornamental castings and other small size parts. Brass with around 40% zinc is called muntz metal. Red brass and yellow brass fall under the category α-brasses, which have 36% or less zinc, and exhibit combined strength and ductility. Brasses with zinc content between 36% and 45% are called β-brasses, which are relatively high in hardness and are brittle. Brasses with over 45% zinc are called γ-brasses, which are difficult to work in both the hot and cold states. A variety of properties can be imparted to brasses by controlling the proportion of copper and zinc, and the addition of small amounts of elements like lead, tin, silicon, aluminum, nickel, phosphorus, and arsenic.

Brasses are produced as cast, forged, machined, stamped, drawn, or spun parts. The comparatively high price of brass is offset by the unique properties that it offers, like high ductility; rapid drawing speeds in presses and dies; lower maintenance cost on dies; ease of plating or use for plating; ease of machining, forming, and casting; high value of scrap; and ability to be alloyed with many metals to give desirable characteristics.

Bronze: Initially, the term bronze referred to copper-tin alloys. However, bronzes now can contain silicon or aluminum as the alloying element instead of tin. Bronzes with tin are called phosphor bronzes because they contain a noticeable amount of phosphorus (~0.3%) from the refining operation. Their strength and hardness increase as the amount of tin increases. The have a low coefficient of friction with most material surfaces. They find application as spring and bearing plate material. Silicon bronze is an important alloy for marine applications and high-strength fasteners. Most of the commercial silicon bronzes contain less than 4% silicon, plus small amounts of other elements like zinc or manganese (usually around 1%). The effect of silicon is to strengthen, harden, and improve the corrosion resistance and electrical resistivity of the alloy. Silicon-bronzes can be easily cast, forged, welded, stamped, rolled, and spun. They find principal use where resistance to corrosion and high strength are required. Aluminum bronzes contain no tin, but 8 to 12% aluminum. Iron is added to aluminum bronzes to increase the strength and hardness. These alloys have excellent corrosion resistance. These are very high-strength alloys and their high corrosion resistance allows them to be used as structural materials. They are also used in valve nuts, cam bearings, impellers, hangers in pickling baths, agitators, crane gears, and connecting rods. They have higher fatigue strength and can be used at high temperatures (up to 750 °F [400 °C]) for short periods of time. Manganese bronzes are similar to aluminum bronzes, but their properties are slightly inferior than aluminum bronze. They are used in marine propellers and fittings, pinions, ball bearing races, worm wheels, gear shift forks, architectural work, rolling mill screw-down nuts and slippers, bridge trunnions, gears and bearings, all of which require strength and hardness. Beryllium bronzes are used where a non-ferrous, non-sparking or good electrical conductor with high strength is required. They are some of the best corrosion-resistant spring materials. They are used in springs of all form, x-ray windows, molds for plastics, and diaphragms. They can be heat treated and shaped at the same time in steel molds.

Cupronickels: Cupronickels contain nickel as the main alloying element. They are ductile, and are primarily hardened and strengthened by cold work. The most important cupronickel alloys contain about 70% copper and 30% nickel. They are used in applications requiring corrosion resistance.

Nickel silvers: Nickel silvers are alloys of copper, nickel and zinc with approximate ranges of 45% to 75% copper, 5% to 30% nickel, and 5% to 45% zinc. The can be ductile and soft, or less ductile and harder depending on their composition. They have moderate strength in the cold worked condition, and thus find application as springs and mechanical components. With the right combination of nickel and zinc, alloys that have the appearance of silver can be obtained; thus the name nickel silvers. They are used for nameplates, bezels, and for silver-plated cutlery and silverware.

Applications

Pure copper is used extensively for cables and wires, electrical contacts, in electric motors, and a wide variety of other parts that are required to pass electrical current. Coppers and certain brasses, bronzes, and cupro-nickels are used extensively for automobile radiators, heat exchangers, home heating systems, panels for absorbing solar energy, and various other applications requiring rapid conduction of heat across or along a metal section. Because of their outstanding ability to resist corrosion, coppers, brasses, some bronzes, and cupro-nickels are used for pipes, valves and fittings in systems carrying potable water, process water, or other aqueous fluids. Copper parts are also used in transportation applications including road vehicles, railroad equipment, aircraft parts and in various other types of heavy equipment, off road vehicles, and machine tools. Typical applications of cold-worked alloys include, springs, fasteners, hardware, small gears, cams, electrical contacts, and components. Copper alloys that contain 1 to 6% lead are widely used for machined parts, especially in screw machines. Plain bearings of copper alloys are used in fractional-horsepower motors, in marine applications, and in very large, heavily loaded journals such as paper mill rolls, railroad train bearings, and steel mill roll bearings. The major alloys of copper that are used in bearings are phosphor bronzes, copper-tin-lead alloys, and manganese, aluminum and silicon bronzes.

D.6.2 Nickel Alloys

A number of other applications for nickel alloys involve the unique physical properties of special purpose nickel-base or high-nickel alloys. These include:

Nickel-chromium alloys that contain more than 15% chromium are used to provide resistance to oxidation and carburization at temperatures exceeding 1400 °F (760 °C). The chromium promotes the formation of a protective surface oxide. The addition of iron to these alloys can help prevent internal oxidation that occurs in atmospheres that are oxidizing to chromium but reducing to nickel. (An example is Incoloy which was introduced as a sheathing material for electric stove elements. This series of alloys has found extensive use in the high-temperature petrochemical environments in catalytic cracking tubes, pigtails and reformer tubes.) Increasing the nickel content in these alloys increases the resistance to carburization, nitriding, and thermal fatigue. Resistance to sulfidation is enhanced by the presence of chromium in the alloy. Nickel-base alloys offer excellent corrosion resistance to a wide range of corrosive media.

Low expansion alloys: Nickel has a profound effect on the thermal expansion of iron and nickel-iron alloys. Consequently, a family of low expansion alloys has been developed, having either very a low coefficient thermal expansion or a uniform and predictable expansion over a reasonably large temperature range. Invar (iron with 36% nickel) has the lowest thermal expansion of the nickel-iron alloys and maintains near constant dimensions during normal variation in atmospheric temperature. Higher nickel amounts result in greater thermal expansion, which allows for specific expansion rates to be selected by adjusting the nickel content. The addition of cobalt to the nickel-iron matrix produces alloys with a low coefficient of expansion, a constant modulus of elasticity, and high strength. These alloy systems have been used by the aerospace industry to design near net-shape components and to provide closer clearance between the tips of rotating turbine blades and retainer rings. This allows for greater power output and fuel efficiencies. Alloys with controllable thermoelastic coefficients are used in spring, pressure sensor and instrumentation applications like bourdon tubing, aneroid capsules, tuning forks, mechanical filters and vibration reeds. Kovar, a low expansion alloy is used in high integrity electronic components for military packages and in lids and closures for hybrid electronic packages. Invar is used in the electronic industry for printed circuit boards, in thermo-mechanical controls and switches, and in cryogenic tanks for handling liquid gases.

Electrical resistance alloys: Several alloy systems based on nickel or containing high amounts of nickel are used in instruments and control equipment to measure and regulate electrical characteristics (resistance alloys) or are used in furnaces and appliances to generate heat (heating alloys). Nickel and its alloys satisfy the primary requirements for resistance alloys (uniform resistivity, stable resistance, reproducible temperature coefficient of resistance, and low thermochemical potential versus copper) as well as the secondary requirements (coefficient of expansion, mechanical strength, ductility, corrosion resistance, and the ability to be joined to other metals by welding, brazing or soldering). They also satisfy the primary requirements of heating alloys (high melting point, high electrical resistivity, reproducible temperature coefficient of resistance, good oxidation resistance in furnace environments, absence of volatile components, and resistance to contamination) as well as the secondary requirements (good elevated-temperature creep strength, high emmisivity, low thermal expansion, good resistance to thermal shock, and good strength and ductility at fabrication temperatures). The types of resistance alloys containing nickel include copper-nickel alloys, nickel-chromium-aluminum alloys, nickel-chromium-iron alloys, and nickel-chromium-silicon alloys. The resistance heating alloys containing nickel include nickel-chromium alloys and nickel-chromium-iron alloys.

Soft magnetic alloys: There are two broad classes of magnetically soft iron-nickel alloys that have been developed. The high nickel alloys (79% nickel, 4% to 5 %

molybdenum, balance iron) which have high initial permeability and low saturation induction and the low nickel alloys (about 50% nickel) that are lower in initial permeability but higher in saturation induction. The high nickel alloys are useful for applications in which power requirements must be minimized such as transformers, inductors, magnetic amplifiers, magnetic shields, tape recorder heads, and memory storage devices. The low nickel alloys are used in rotors, armatures, and low level transformers.

Shape memory alloys: Nickel-titanium alloys (50% nickel and 50% titanium) have shape-memory characteristics.

Applications

Nickel and nickel alloys are used for a wide variety of applications, the majority of which involve corrosion resistance and/or heat resistance. Some of the typical applications of nickel and its alloys include: disks, combustion chambers, bolts, casings, shafts, exhaust systems, cases, blades, vanes, burner cans, afterburners, and thrust reversers in aircraft gas turbines; bolts, blades, and stack gas reheaters in steam turbine power plants; turbochargers, exhaust valves, hot plugs, and valve seat inserts in reciprocating engines; hot-work tools and dies in metal processing; dentistry uses and prosthetic devices in medical applications; aerodynamically heated skins and rocket engine parts in space vehicles; trays, fixtures, conveyor belts, baskets, fans, and furnace mufflers in heat-treating equipment; control rod drive mechanisms, valve stems, springs, and ducting in nuclear power systems; bolts, fans, valves, reaction vessels, piping, and pumps in chemical and petrochemical industries; scrubbers and flue gas desulfurization equipment (liners, fans, stack gas reheaters, and ducting) in pollution control equipment; ovens, afterburners, and exhaust fans in metal processing mills; heat exchangers, reheaters, and piping in coal gasification and liquefaction systems; and tubing, doctor blades, bleaching circuit equipment, and scrubbers in the pulp and paper mills.

D.6.3 Tin Alloys

The manufacture of inorganic and organic chemicals containing tin constitutes one of the major uses of metallic tin. Tin chemicals are used for such widely diversified applications as electrolyte solutions for depositing tin and its alloys; pigments and opacifiers for ceramics and glazes; catalysts and stabilizers for plastics; pesticides, fungicides, and antifouling agents in agricultural products, paints, and adhesives; and corrosion inhibiting additives for lubricating oils.

Fusible alloys are any of the more than one hundred white metal alloys that melt at relatively low temperatures. Most commercial fusible alloys contain bismuth, lead, tin, cadmium, indium, and antimony, and special alloys of this class may also contain significant amounts of zinc, silver, thallium, or gallium. These alloys find important uses in automatic safety devices such as fire sprinklers, boiler plugs, and furnace controls. Under ambient temperature, these alloys have sufficient strength to hold parts together, but at a specific elevated temperature the fusible alloy link will melt, thus disconnecting the parts.

Solders: Tin is an important constituent in solders because it wets and adheres to many common base metals at temperatures considerably below their melting points. Tin is alloyed with lead to produce solders with melting points lower than those of either tin or lead. Small amounts of various metals, notably antimony and silver, are added to tin-lead solders to increase their strength. These solders can be used for joints subjected to both high and subzero temperatures. Commercially pure tin is used for soldering side seams of cans for special food products and aerosol sprays. The electronics and electrical industries employ solders containing 40 to 70% tin that provide strong and reliable joints under a variety of environmental conditions. High tin solders are used for joining parts of electrical apparatuses because their electrical conductivity is higher than that of high lead solders. High tin solders are also used where lead may be a hazard (when in contact with foodstuffs or in potable-water plumbing applications). Some solders are used to fill crevices at seams and welds in automotive bodies, thereby providing smooth joints and contours. Tin-zinc solders are used to join aluminum. Tin-antimony and tin-silver solders are employed in applications requiring joints with high creep resistance, and in applications requiring a lead-free solder composition, such as potable-water plumbing. Also, tin solders that contain 5% antimony (or 5% silver) are suitable for use at higher temperatures than are tin-lead solders. Impurities in solders can affect their wetting properties, flow within the joint, melting temperature of the solder, strength capabilities of the joints, and oxidation characteristics of the solder alloys.

Pewter: Pewter is a tin-base white metal containing antimony and copper. Originally, pewter was defined as an alloy of tin and lead, but to avoid toxicity and dullness of finish, lead is excluded from modern pewter. These modern compositions contain 1 to 8% antimony and 0.25 to 3% copper. Pewter casting alloys usually are lower in copper than pewters used for spinning hollow ware and thus have greater fluidity at casting temperatures. Pewter is malleable and ductile, and it is easily spun or formed into intricate designs and shapes. Pewter parts do not require annealing during fabrication, have good solderability. Pewter can be formed either by rolling, hammering, spinning or drawing. Much of the costume jewelry produced today is made of pewter alloys centrifugally cast in rubber or silicone molds. Pewter tarnishes in soft water, with the production of a visible film of interference-tint thickness. It does not tarnish in hard water. Pewter is attacked by dilute hydrochloric and citric acids in the presence of air. Typical pewter products include coffee and tea services, trays, steins, mugs, candy dishes, jewelry, bowls, plates, vases, candlesticks, compotes, decanters, and cordial cups.

Hard tin (99.6% tin - 0.4% copper) is used for collapsible tubes and foils. Hard tin is resistant to attack by foodstuffs, medicinal products, cosmetics, and artist's colors.

Tin foil (92% tin - 8% zinc) is used for food packaging. Its suitability for this application is indicated by, for example, bottle-capping tests with milk that showed that this alloy is only slightly soluble and has no effect on the milk.

Battery grid alloys: Lead-calcium-tin alloys have been developed for storage battery grids, largely as replacements for antimonial-lead alloys. The use of the lead-calcium-tin alloy with up to 1.3% tin has substantially reduced gassing, and thus batteries with grids made of these alloys do not require periodic water additions during their working life.

Copper alloys: Copper-tin bronzes are used for structural and decorative purposes. True bronzes contain up to 10% of tin and small amounts of phosphorus. Quaternary bronzes contain 5% tin, 5% zinc, 5% lead, and a balance of copper and are used for general-purpose casting applications requiring reasonable strength and soundness, such as gears, pumps, and automotive fittings. Special copper-base alloys with 20 to 24% tin have been used for cast bells of excellent tonal qualities. Spinodal copper-nickel-tin alloys containing 2 to 8.5% tin have excellent elastic properties and have replace tin-free copper-nickel alloys in some spring and electrical contact applications. In addition to these uses in copper-base alloys, small quantities of tin (0.75 to 1.0%) are added to copper-zinc alloys (brasses) for increased corrosion resistance

Titanium alloys have tin to strengthen them without increased embrittlement.

Zirconium alloys have tin added to enhance its high-temperature strength. A commercial series of corrosion resistant zirconium alloys containing 0.15 to 2.5% tin has been developed for nuclear service.

D.6.4 Cobalt Alloys

Cobalt is a tough silver-gray magnetic metal that resembles iron and nickel in appearance and in some properties. Cobalt is useful in applications that utilize its magnetic properties, its corrosion resistance, its wear resistance and/or its strength at elevated temperatures. Many of the properties of these alloys arise from the strengthening effects of the alloying elements chromium, tungsten and molybdenum. Some cobalt-base alloys are also biocompatible, which has prompted their use as orthopedic implants. The wear-resistant alloys form the single largest application area of cobalt-base alloys.

Cobalt-base alloys are not as widely used as nickel-base alloys in high temperature applications. However, their excellent resistance to sulfidation and strength at high temperatures find use in some applications where nickel-base alloys cannot perform as effectively. Cobalt is also used as an alloying element in many nickel-base high-temperature alloys. Modern cobalt-base alloys contain tungsten and moderate quantities of nickel, low amounts of carbon, and some rare-earth metals.

Cobalt base wear resistant alloys and high temperature alloys do offer some resistance to aqueous corrosion, but fall well short of the nickel-chromium-molybdenum alloys in corrosion resistance. This has lead to the development of cobalt-base low carbon, cobalt-nickel-chromium-molybdenum alloys that have excellent corrosion resistance along with the attributes of normal cobalt base alloys (resistance to various forms of wear, and high strength over a wide range of temperatures).

Cobalt-base wear resistant alloys have moderately high yield strengths and hardnesses. Their ductility varies inversely with the amount of carbon in them. These alloys are used in moderately corrosive and/or elevated temperature environments. Typical applications of cobalt-base wear-resistant alloys are in the automotive industry in engine valve seating surfaces; in the power industry in control valve seating surfaces, and steam turbine erosion shields; in the marine industry in rudder bearings; in the steel industry in hot shear edges, and bar mill guide rolls; in the chemical processing industry in control valve seating surfaces, plastic extrusion screw flights, pump seal rings, and dry battery molds; in the pulp and paper industry in chain saw guide bars; in the textile industry in carpet knives; and in the oil and gas industry in rotary drill bearings.

Other than the cobalt-base alloys, cobalt finds importance as an ingredient in paint pigments, nickel-base superalloys (where it helps to strengthen the alloy), cemented carbides and tool steels (where it provides a suitable bonding matrix for tungsten carbide particles), magnetic materials (where it provides resistance to demagnetization), and artificial gamma-ray sources (in the form of its radioactive isotope cobalt-60).

D.7 Refractory Metals

D.7.1 Molybdenum Alloys

Molybdenum is used as an alloying element in cast irons, steels, heat-resistant alloys, and corrosion-resistant alloys to improve hardenability, toughness, abrasion resistance, corrosion resistance, and strength and creep resistance at elevated temperatures. Molybdenum and its alloys have high thermal conductivity and low specific heat. In its pure form or as a base alloy, molybdenum is used in a wide range of industries in tools and components that can perform satisfactorily at high temperatures or under severe abrasive or corrosive conditions. Molybdenum has particularly good resistance to corrosion by mineral acids, provided that oxidizing agents are not present. The metal is relatively inert in carbon dioxide, hydrogen, ammonia and nitrogen atmospheres at temperature up to about 2000 °F (1095 °C); it is also relatively inert in reducing atmospheres containing hydrogen sulfide. Molybdenum has excellent resistance to corrosion by iodine vapor, bromine and chlorine up to clearly defined temperature limits and good resistance to attack by several liquid metals, including bismuth, lithium, magnesium, potassium, and sodium.

<u>Applications</u>

Molybdenum is used as a filler metal for brazing tungsten and for resistance heating elements in electric furnaces that operate at temperatures up to 4000 °F (2205 °C). Molybdenum is important in the missile industry, where it is used for high-temperature structural parts such as nozzles, leading edges of control surfaces, support vanes, struts, reentry cones, heat-radiation shields, heat sinks, turbine wheels, and pumps. Molybdenum alloys are particularly well-suited for use in airframes because of their high stiffness, retention of mechanical properties after thermal cycling, and good creep strength.

In the metal working industry, molybdenum is used for die-casting cores; for hot work tools such as piercer points and extrusion and isothermal forging dies; for boring bars, tool shanks, and chill plates; and for tips on resistance welding electrodes. It is also used for cladding, for equipment for truing grinding wheels, for molds, and for thermocouples. Molybdenum has also been useful in the nuclear, chemical, glass, and metallizing industries. Pure molybdenum has good resistance to hydrochloric acid and is used for acid service in the chemical process industries.

Molybdenum and its alloys can be forged using either open or closed dies, can be fabricated in sheet form by conventional rolling and cross-rolling processes, and are readily extruded into a number of shapes including tubes, round to round bars, round to square bars, and round to rectangular bars. Large tubes and rings are fabricated from back extruded solid billets. Additional ring-forming operations are undertaken via ring-rolling.

D.7.2 Tungsten Alloys

Tungsten is combined with cobalt as a binder to form a cemented carbide that is used in cutting and wear applications. The high melting point of tungsten makes it an obvious choice for structural applications exposed to very high temperatures. Tungsten is used at lower temperatures for applications that can take advantage of its high elastic modulus, density, or shielding characteristics. At room temperatures, tungsten is resistant to most chemicals, but it can be easily dissolved with a solution of nitric and hydrochloric acids. At higher temperatures, around 1830 °F (1000 °C), tungsten becomes more prone to attack by acids, gases such as chlorine, water vapor, iodine, bromine, and carbon monoxide, as well as various metals. Tungsten has high tensile strength and good creep resistance. However, its high density, poor low-temperature ductility, and strong reactivity in air limit its usefulness. Wrought tungsten has high strength, strongly directional mechanical properties, and some room temperature toughness. Two commercially produced tungsten alloys are: tungsten-molybdenum and tungsten-rhenium. Alloying with rhenium improves the tensile strength of tungsten, although small additions of rhenium cause softening of tungsten-rhenium. Alloying tungsten with molybdenum has a softening effect that is proportional to the molybdenum content.

Tungsten and tungsten alloys can be pressed and sintered into bars and subsequently fabricated into wrought bar, sheet, or wire. A class of tungsten alloys called tungsten heavy metals (tungsten-nickel-copper and tungsten-nickel iron alloys) have been developed that are relatively ductile and with lower melting points, good machinability and good mechanical properties. Tungsten and tungsten alloys are used extensively in applications for which a high density material is required, such as kinetic energy penetrators, counterweights, flywheels, and governors. Other applications include radiation shields and x-ray targets. In its wire form tungsten is used extensively for lighting, electronic devices, and thermocouples. Tungsten chemicals are used for organic dies, pigment phosphors, catalysts, cathode-ray tubes, and x-ray screens.

PART III PLASTICS

PART IIIa THERMOPLASTICS

D.8 Partially Crystalline

D.8.1 Polyethylene

Polyethylene has a low heat conductivity and ranges from very flexible to stiff. It is completely free from decomposition at normal molding temperatures and pressures. There is a wide plasticity range and the material becomes molten and moldable over a wide range of conditions. Polyethylene has absolutely no moisture absorption and does not require any storage precautions or drying operations. It can, however, develop static electrical charges and attract dust particles and other atmospheric contaminants. Polyethylene is usually supplied in a pellet form. Clean and undegraded polyethylene can be readily reground and reused. There is no restriction on the number of time it can be reused. Although polyethylene does not degrade at normal molding temperatures and pressures, poor heat gradients in the mold and the heater can cause polyethylene to break down and the molds to crack. The shrinkage of polyethylene is generally high, but is greater in the direction of flow than the direction across flow. The lack of additives such as platicisers and lubricants reduces the chance of any volatiles being present in the molds. Polyethylene is used over a wide range of applications, but particularly in the field of consumer items such as buckets, bowls, baby baths, pedal bins, watering cans, funnels, mixing bowls, and an enormous number of other items. Industrial used of polyethylene includes low service temperature insulation work. Its toughness is made use of in damage protection uses ranging from kick plates in buses to sealing plugs on valves and pipe fittings. It is also used in packing.

D.8.2 Polypropylene

Polypropylene has a low density. Its products are characterized by rigidity, good surface hardness, reasonable environmental stress resistance, and also the property of molecular orientation in thin flexed sections. This gives a good tear-strength and has led to the use of these materials for hinges. The resilience of polypropylene makes it possible to design clip fastening by undercuts. Polypropylene is available as natural (translucent) granules or as small beads (polymer) for dry-coloring. A full range of colors is possible. Pre-drying is unnecessary, except to remove condensed moisture. Heating of any kind is not recommended for long periods since this can cause the material to degrade. To avoid long cooling cycles, temperatures should be kept to a minimum range of 392-572 °F (200-300 °C). Polypropylene cools much faster than polyethylene and is an important factor that must be considered while designing these parts. Stresses may develop during cooling, accompanied with distortion of the part and care must be taken to prevent this. Polypropylene is a 'notch-sensitive' material and sharp corners should be avoided and instead small radii should be provided. Due to the inertness of polypropylene, it is very difficult to cement.

D.8.3 Acetals

Acetals are a relatively new thermoplastic, first becoming available in 1960. In appearance they are similar to nylon, with which they compete in applications such as gears, bearings, hardware components and business machine assemblies. The resin is a linear polymer of formaldehyde that is highly crystalline. Acetals may exist as a homopolymer (e.g., Delrin) or as a copolymer (e.g., Celcon).

Properties

Acetals have excellent mechanical properties which enable them to be used in place of metals in many applications. They have a high tensile strength which is retained over at least several years in air/water exposures at temperatures of 95 °C. They have high impact resistance which is only slightly affected by sub-zero temperatures. Their stiffness is high, and creep and fatigue resistance exceed that of any other thermoplastic. The coefficient of friction is low and abrasion resistance is comparable to metals. Acetals resist solvents and most alkalis but are attacked by acids. Colorability is good and discoloration by industrial oils and grease is not a problem. Moisture absorption is low, weatherability is good, but short-term exposure to ultraviolet radiation causes chalking of the surface, while prolonger exposure affects strength.

D.8.4 Nylons

Nylon(Du Pont) is a household word throughout the world. Nearly everyone is familiar with nylon fibers used for wearing apparel, brush bristles and carpet. Less widely known are the commercial and industrial uses of nylon molding resins, coatings, adhesives and films. Polyamide is the chemical term used to describe linear polymers in which the structural units are connected by amide groups. The first polyamide produced in continuous filament form was used for hosiery and undergarments as a replacement for natural silks. The trade name `Nylon' was adopted, but today the term nylon is used generally to describe any polyamide capable of forming polymers. The types of nylons are so numerous that a numbering system to describe them has been adopted. It involves digits denoting the number of carbon atoms in the parent chemicals.

Properties

General characteristics of nylons are as follows:

Transparency: The natural state of nylon molding and extrusion resins is translucent, beige or off-white. Extruded films find applications in prepared food packaging where foods are boiled in the package.

Anti-drag and Anti-friction Properties: Extruded nylons provide abrasion and cut-through resistance and they can be pulled through complicated conduit paths because of inherent anti-drag properties. Low friction, a property common to all nylons, makes them suitable for gears, rollers, cams, door latch components and many other moving or bearing parts.

Heat Resistance: Most grades are self-extinguishing and impart an odor of burning wool. Heat resistance based on deflection under load is from 65 to 180 °C. Continuously exposed to dry heat nylons embrittle at about 120 °C.

Moisture Absorption: All nylons absorb moisture to a degree depending on formulation, and reach an equilibrium between 0.20 and 0.25%. Type selection and design tolerances thus become critical when moving parts are required to operate in a humid environment.

Chemical Resistance: Nylons are generally resistant to many chemicals, notably gasoline, liquid ammonia, acetone, benzene and organic acids. They are attacked, lose, strength and swell when exposed to chlorine and peroxide bleaches, nitrobenzene and hot phenol. Nylons are not recommended for extended exposure to ultraviolet light, hot water and alcohols. They are resistant to moth larvae, fungus and mildew.

Melting Point: Unlike most thermoplastics, nylons are highly crystalline with sharply defined melting points at which they become extremely fluid and free flowing. Nylons degrade rapidly when held too long in extruder heating chambers or injection machines. Parts are discolored and lose strength and/or chemical resistance.

D.8.5 Florocarbons

Fluorocarbons are compounds of carbon in which fluorine instead of hydrogen is attached to the carbon chain. The resulting compounds are very stable to heat and chemicals. Fluorocarbon plastics include polytetrafluoroethylene (PTFE or Teflon[Du Pont De Nemours & Co. Inc.]), fluorinated ethylene propylene (FEP) and polyvinylidene fluoride (PVF).

D.8.6 Polyimides

Polyimides are a family of some of the most heat and fire resistant polymers known. Their excellent retention of mechanical and physical properties at high temperature is due to the nature of the aromatic raw materials used in their manufacture. Polyimides are formulated as thermosets and thermoplastics. Moldings, laminates and resins are generally based on thermosets. Thin film products such as adhesives and coatings are usually derived from thermoplastic polyimide resins.

Laminates utilize continuous reinforcements such as woven glass and quartz fabrics and boron and graphite fibers. Molding compounds contain chopped glass or asbestos or particulate fillers such as graphite powder. Polyimide films and wire enamels are generally unfilled. Coatings may be pigmented or PTFE-filled to give better lubrication. Adhesives generally contain aluminum power to provide a closer match to the thermal expansion characteristics of metal substrates and to improve heat dissipation.

Polyimide parts are fabricated by techniques that range from extrusion and powder metallurgy to injection, transfer and compression molding methods. Generally the greater the heat resistance of a polyimide, the more difficult it is to manufacture. Parts and laminates can operate continuously in air at 280 °C. They can withstand short exposures to temperatures as high as 500 °C. Glass fiber reinforced polyimides retain 70% of their flexural modulus at 250 °C. Creep is almost nonexistent even at high temperatures.

Polyimides have good wear resistance and low coefficients of friction. Both of these properties are improved by using PTFE fillers. Self-lubricating parts containing graphite powders have flexural strengths above 70 MPa, which is considerably higher than most thermoplastic gearing materials. Electrical properties are outstanding over a range of temperature and humidity conditions. Parts are unaffected by exposure to dilute acids hydrocarbons, esters, ethers and alcohols. They are attacked by dilute alkalis and concentrated organic acids.

Polyimide film has good mechanical properties to 600 °C. An outstanding features is that, at 4 °K, polyimide film can be bent around a 6 mm mandrel without breaking, and at 500 °C its tensile strength is 30 MPa. Polyimide adhesives maintain useful properties for over 12,000 hours at 280 °C and for 100 hours at 370 °C. Resistance of adhesives to combined heat and salt water is excellent. Molded glass reinforced polyimides are used in jet engines and in high temperature electrical connectors. High speed, high load bearings for business machines and computer printout terminals use self-lubricating polyimides. Other applications include bearing cages for gyroscopes and air compressor piston rings.

D.8.7 Cellulosic Materials

These are a wide range of compounds which have cellulose as the base material. The most popular of the cellulosic materials is cellulose acetate. Cellulose acetate is characterized by high resilience, high toughness, high surface finish, good impact strength, low heat resistance, low moisture resistance, and poor dimensional stability; though it shrinks uniformly in both directions. It however is not inflammable like some other cellulosic materials, e.g. cellulose nitrate. It is available in the chip or granular form. It can be transparent or opaque. Absorbed moisture improves the flow property of the material, but leads to poor molding quality; care must therefore be taken to prevent contact with moisture. "Soft grades" of cellulose acetate flows easily in the molten form while the "hard grades" flow less easily. Cellulose acetate should not be overheated as this will result in the expulsion of certain volatile constituents and additives, which will result in brittle molds that have a poor surface finish. It is possible to obtain improved cellulose acetates that have increased heat resistance, higher impact strength, greater dimensional stability, lower water absorption, and reduced inflammability. However, improvements in one of these properties will be at the expense of an other. Cellulose acetate can be successfully reground and re-used, though it is a little harder than the virgin material. However, there is a limit to the number of times that the material can be recycled.

D.9 Amorphous

D.9.1 Polycarbonates

Polycarbonates possess very high impact strength, glass clear transparency, heat resistance, high dimensional stability and chemical resistance. These properties make polycarbonates ideal for vandal-proof public lighting fittings, windows and doors. Risk of breakage can be virtually eliminated by glazing with Lexan(G.E. Plastics Group), a polycarbonate sheet several hundred times stronger than glass. It resists hammers, bricks, sparks, sprayed liquids and heat.

Polycarbonates are also available in a variety of colors produced with pigments. They have good creep resistance and are excellent electrical insulators. Because of its high heat resistance (up to 145 °C) polycarbonates are one of the few thermoplastics suitable for use with high output lighting where temperatures can exceed 100 °C. They are also nonflammable and self-extinguishing. Under excessively high temperature, however, polycarbonate breaks down with the evolution of carbon dioxide gas.

Being resilient, the material resists denting. Its high rigidity, often without the need for reinforcing ribs, allows design freedom; foam molding allows it to be produced in many shapes. Structural foam polycarbonate has a strength-to-weight ratio between two and five times that of conventional metals. Typical applications include automotive interior panels and external bumper extensions, appliance and business machine housings and bins for industry.

Solid opaque polycarbonate grades are widely used for high impact applications such as crash helmets, photographic equipment and in electronics and electrical equipment. They are also used for the production of binocular bodies because of their breakage resistance and for water pumps because of their corrosion and abrasion resistance.

D.9.2 Acrylonitrile Butadiene Styrene (ABS)

Acrylonitrile butadiene styrene (ABS) plastics are a family of opaque thermoplastics offering a balance of properties, the most outstanding being impact resistance, tensile strength and scratch resistance.

Properties

The ABS plastics are ductile and are characterized by high impact strength, moderate tensile and compressive strengths, marked dimensional stability and extremely good corrosion and chemical resistance. They are very rigid and retain their properties over a wide range of temperatures, frequently as low as -40 °C for refrigerator parts. ABS is easily electroplated. Flow characteristics give good moldability and colors available are unlimited with high gloss stain resistant finishes. Weatherability is outstanding - most environments have little or no effect on ABS, although prolonged strong sunshine may cause embrittlement. Resistance to creep and cold flow is moderate to good. Acoustic damping characteristics are excellent. Flammability is classified as slow burning, but ABS may be made flame resistant by blending with polyvinyl chloride.

D.9.3 Polystyrene

Polystyrene is one of the most popular and widely used thermoplastics in the industry. It is cheap in its basic form, and can be supplied in any color ranging from crystal clear to opaque black. It can be supplied in both powder and solid cube form. The moisture absorption of polystyrene is much lesser than that of cellulose acetate. However, due to its dryness, it is liable to develop a high static charge that tends to attract dust, dirt, and other atmospheric particles from its surroundings and should, therefore, be covered at all times to prevent contamination. Polystyrene is easier to work and mold than cellulose acetate. Moldings made from polystyrene have bright colors, hard surfaces, excellent dimensional stability, freedom from distortion, and a metallic noise when dropped on a solid surface. These moldings are brittle and when broken, are likely to show a jagged fracture with sharp edges. Polystyrene is free from taste and smell, non-toxic when in contact with food, non-contaminating when in contact with toilet preparations and does not support the growth of molds or fungi. It can be reground and reused. Polystyrene is resistant to most inorganic materials, but is attacked by organic solvents which render it useless. Advantage can, however, be taken of this property of polystyrene and items made of polystyrene parts can be fabricated using organic solvents to cement these pieces together. An inherent problem in polystyrene parts is molded-in strain. In order to cater for special applications, polystyrene can be modified. High molecular weight grades of polystyrene are used to improve flexibility and strength. Heat resistant grades of polystyrene can resist distortion up to 205-210 °F (96-99 °C); however higher molding temperatures are required. Filled grades of polystyrene use mica and glass fiber as fillers to enhance the electrical properties and impact strength. Flame-retardant grades find applications in products such as housing for motors, television cabinets, and appliance parts. An interesting use of polystyrene is in the metal casting industry, where patterns, gates, and risers are made of polystyrene which evaporate when the hot molten metal is poured into the mold; the pattern is replaced with an exact duplicate in metal.

D.9.4 Polyvinyl Chloride

Polyvinyl chloride, better known by its acronym, PVC, is one of the most widely used plastics. PVC is made by reacting acetylene gas with hydrochloric acid in the presence of a catalyst. PVC is produced by extrusion, compression molding, blow molding, calendering, injection molding, powder coating, and liquid processing. Plasticized PVC is more commonly used as vinyl. In this form, it has low strength and is used for imitation leather, decorative laminates, upholstery, wall coverings, and a number of other consumer products. It is used in the industry in the form of flexible tubing and for corrosion-resistant coatings applied to metals. PVC finds use as insulation on electrical tool handles, and wires. It is preferred over plastics for these types of applications because it is not inflammable and does not sustain combustion, and has good dielectric properties. Rigid PVC (without the plasticizer) has sufficient strength and stiffness to almost qualify as an engineering plastic. It is a thermoplastic with good abrasion resistance, moldability, and fabricability. In the extruded form, rigid PVC is widely used for low-cost piping for cold water or chemicals. Chlorinated PVC (CPVC) is used for hot water piping (temperatures up to 180 °F [82 °C]). In the industry, PVC is used for guards, ducts, tanks, fume hoods, and similar components, that require corrosion resistance. PVC is very resistant to many acids and bases, but it has poor resistance to organic solvents and organic chemicals. PVC has poor toughness and notch sensitivity. PVC can be copolymerized with a number of other polymers to improve and/or modify its properties. Other PVC products include pump parts, handles, plumbing pipes and elbows, building siding, window frame, gutters, interior molding and trim, shower curtains, refrigerator gaskets, appliance components, and auto tops. PVC is formed into sheets used to enclose and seal packages for storage under dehydrated conditions. It is made into filaments that are woven into warm fabrics, window screen, and shoe fabrics.

D.9.5 Polyurethane

Polyurethane is best known as polyurethane-foam. Polyurethane is more expensive than nylon, has lower heat resistance, is not as tough, is more flexible, has better chemical properties, has better chemical resistance, a much lower moisture absorption, and better dimensional stability. Due to its heat sensitivity, it can degrade if handled improperly. It is also unwise to use non-ferrous metal molds or have non-ferrous inserts in the mold as any degradation that may be present will be accelerated. Polyurethane tends to stick to the molds, especially when there are ribs and fillets. Great care has to be taken to chose the ejection points of molded parts to ensure that the molds do not break. The range of applications of polyurethane is wide, with special emphasis on jobs that require resistance to impact and resilience, such as picker hammers, and other weaving parts.

PART IIIb THERMOSETS

D.10 Highly Crosslinked

D.10.1 Alkyds

Alkyds are thermoset molding materials. They are made by combining a monomer with unsaturated polyester resins and additives or fillers.

Properties

Like most thermosets, alkyds are hard and stiff and retain their mechanical and electrical properties at elevated temperatures. Their properties depend greatly on the fillers and manufacturing processes used. Typically, tensile strength is low, whereas compressive strength is much higher, by a factor of 4-5. Outstanding properties are their arc and track resistance, low moisture absorption and retention of electrical properties when wet. Only small changes in dielectric loss factor are caused by temperature. Dimensional stability is very good.

D.10.2 Epoxies

An epoxy resin is defined as any molecule containing more than one *-epoxy group and capable of being converted to a useful thermoset form. The term is used to indicate the resins in both the thermoplastic (uncured) and thermoset (cured) state. Cured epoxies are a major structural type in plastics technology.

Properties

A number of properties have led to the rapid growth in the use of epoxy resins and their use in many industries.

Liquid Resins: These are low-viscosity liquids which readily convert to the thermoset phase upon mixture with a curing agent. There are other liquid resins -

acrylics, phenolics, polyesters, etc. - which cure in a similar fashion, but epoxy resins possess a unique combination of properties.

- Low viscosity. The liquid resins and their curing agents form low-viscosity, easy-to-process systems.
- Easy cure. Epoxy resins cure quickly and easily at practically any temperature from 5 to 150 °C depending on selection of curing agent.
- Low shrinkage. One of the most important and advantageous properties of epoxy resins is their low shrinkage during cure. Epoxy resins react with very little rearrangement and with no volatile by-products.
- High adhesive strengths. Epoxy resins are excellent adhesives. The best adhesive strengths in contemporary plastics technology are obtained without the need for long curing times or high pressures.
- High mechanical properties. The strength of properly formulated epoxy resins usually surpasses that of other casting resins. This is in part due to their low shrinkage, which minimizes curing stresses.
- High electrical insulation.
- Good chemical resistance. The chemical resistance of cured epoxy resin depends considerably on the curing agent used. Outstanding chemical resistance can be obtained by proper specification of the material.
- Versatility. The basic properties may be modified in many ways: by the blending of resin types; by the selection of curing agents;and by the use of modifiers and fillers.

Solid Resins: The chief use of solid epoxy resins is in solution coatings. The high molecular weight materials are cooked with conventional drying oils or reacted with other resins resulting in toughness, scuff resistance and chemical resistance. Room temperature curing films have been produced which provide properties equal to or exceeding those of many baked-type finishes. The excellent adhesion of epoxy resins, ease of cure, mechanical strength and high chemical resistance are advantages of the solid and liquid resins.

Applications

Because of their versatility epoxies are used in numerous applications such as:

- Adhesives for aircraft honeycomb structures, for paintbrush bristles, and for concrete topping compounds.
- Body solders and caulking compounds for repair of plastic and metal boats, automobiles, etc.
- Casting compounds for fabrication of short-run and prototype molds, patterns and tooling.
- Caulking and sealant compounds in building and highway construction applications and where high chemical resistance is required.
- Potting and encapsulation compounds, impregnating resins and varnishes for electrical and electronic equipment.
- Laminating resins for airframe and missile applications, for filament-wound structures and for tooling fixtures.
- Epoxy-based solution coatings are used as maintenance and product finishes, marine finishes, masonry finishes, structural steel coatings, aircraft finishes, automotive

primers, can and drum linings and in many other industrial applications.

D.10.3 Phenolics

Phenolic resins are among the oldest of plastics and were the first to be commercially exploited. They are used principally in reinforced thermoset molding materials. Combined with organic and inorganic fibers and fillers, the phenolics provide dimensionally stable compounds with excellent moldability.

Phenolics are formed by compression and injection molding and extrusion. Injection molding usually provides the fastest cycle time, but it may not produce the best properties. For example, in long fiber filled compounds, compression molding gives the greatest strengths. Phenolic resins are used as bonding and impregnating materials. Bonding resins are available as pure compounds, but are more often formulated with elastomers and fillers to provide special properties. Phenolics are used in laminates, molding, surface coatings and adhesives. Laminates are usually reinforced with paper, fiber or cloth.

Properties

Phenolic molding compounds are characterized by low cost, superior heat resistance, high heat distortion temperature, good flame resistance, excellent dimensional stability, good water and chemical resistance, and excellent moldability. Phenolic compounds are classified as general purpose, non-bleeding, heat resistant, impact, electrical, and special purpose. Most compounds are black.

D.10.4 Polyesters

The polyester resins are copolymers of a polyester and are usually styrene. They have good strength, toughness, and resistance to chemical attack; low water absorption, and the ability to cure at low pressures and temperatures. These resins have wide applications in low-pressure laminates. Here, the unpolymerized resin can be ladled onto the laminating fabric and subsequent cure can be completed at temperatures as low as 160 °F (70 °C). One wide spread application of this family of thermosetting plastics is the manufacture of boat hulls, using glass fibers as the laminating material and a polyester as the resin.

Alkyd is a polyester resin that is useful in applications requiring high-temperature electrical properties, arc-track resistance, and dimensional stability. Depending on its fibrous reinforcement, this plastic has flexural strength from 8 to 24 ksi and tensile strength from 5 to 15 ksi. This family has poor chemical resistance and low resistance to hydrolytic degradation. The material is available in both granular and pellet form,. The principle use of this thermosetting plastic is in connection with such products as circuit breakers, transformer housings, distributor caps, rotors, etc.

Polybutylene terephthalate (PBT) is a polyester-type resin that provides high heat resistance, good mechanical strength and toughness, general chemical resistance, good lubricity and wear resistance, low moisture absorption, and eye appeal. It is mainly fabricated using injection molding. When reinforced with glass, its tensile strength approaches 20 ksi. Some of the most significant applications of PBT include automotive body components, ignition components, automotive window and door hardware, transmission components, switches, relays, motor brush holders, fuse holders, terminal blocks, food processor blades, fans, gears, and frame and bracket parts.

Polyethylene terephthalate (PET) is a typical polyester that is used to a large extent in blow molding operations. The key properties of PET include excellent gloss and clarity, high toughness and impact strength, good chemical resistance, low permeability to carbon-dioxide, good processability, and good dimensional stability. PET has a melting point of 477.6 °F (247 °C) and a density of (1.4 gms/cc). PET is offered in the market in the form of chops or pellets, either dried or not. At high processing temperatures, moisture content can cause degradation, reducing the mechanical properties. Therefore, PET must be dried before processing. The significance of PET in the bottle or packaging market was achieved through plastic blow molding technology. Its major applications are containers for carbonated beverages and other drinks, and pharmacy containers with volumes of from a few milliliters up to about 30 liters.

D.11 Lightly Crosslinked

D.11.1 Silicone Resins

Silicone resins have excellent resistance to heat, water, and certain chemicals. The resins are usually filled or used in laminated parts. Good physical properties are maintained from 450 to 500 °F (232 to 260 °C). This family of synthetic polymers is partly organic and partly inorganic. Silicones are classified as fluids, elastomers, and resins. Thus, silicone polymers may be fluid, gel, elastomeric, or rigid in their final form. The properties that make silicones attractive to engineering include low surface tension, high lubricity with rubber and plastic surfaces, excellent water repellency, good electrical properties, thermal stability, chemical inertness, and resistance to weather. Silicone fluids are used mainly in the plastics and rubber industry as mold-release agents. When added to organic plastics in molding, they provide water repellency, abrasion resistance, lubricity, and flexibility. Silicone rubbers are used to make seals, gaskets, tubing, hoses, wire insulation, coated fabrics, contact lenses, and artificial toe and finger joints. Silicone resins and composites provide thermal stability to temperatures up to 572 °F (300 °C). Silicones are important in the printing industry because they have a unique ability to transfer ink to other materials; nothing sticks to them.

D.11.2 Acrylics

Acrylics are thermoplastics which offer excellent optical characteristics, resistance to environmental conditions and ease of forming. They are manufactured from methyl methacrylate monomers found in the by-products of petroleum, agricultural and synthetics industries and are copolymerized for form acrylics such as polymethyl methacrylate, known by trade names such as Lucite(Du Pont De Nemours & Co. Inc.), Perspex(DeutscheICI GmbH) and Plexiglass(Rohm & Haus Co.).

Properties

Acrylics transmit about 92% of light and have a high refractive index. They offer very good dimensional stability and are serviceable to 110 °C; however, they show a large thermal expansion - about seven times that of steel. Resistance to weathering is excellent but high intensity ultraviolet light exposure produces crazing, which may be alleviated by annealing. High tensile strength and good impact resistance enhance its usefulness. Acrylics are unaffected by alkalis, industrial oils, inorganic solvents and weak acids or alcohol, but concentration of acid or alcohol results in deterioration. Moisture absorption is low.

D.11.3 Rubbers

Rubber is the term that is applied to substances, either natural or synthetic, that are characterized by exceptional elastic deformity. Properly prepared rubbers can deform more than 200% of their original length when stretched and can return to their original length when the stress is removed. Thus, in addition to high elasticity, rubbers possess high resilience.

Natural rubber: Natural rubber is not used in the form in which it is extracted from the rubber producing plants. In this state it is temperature sensitive, soft in summer and hard in winter and the fluid properties are predominant. Natural rubber is, therefore, vulcanized. Vulcanization that involves the addition of sulfur to rubber to improve the links between the various molecules and helps form stronger bonds, thus reinforcing the solid properties of natural rubber. Carbon, silica, magnesia, and other minerals are used in a finely divided form to reinforce the rubber. Ingredients are also added to natural rubber to minimize attack by oxygen, ozone, and sunlight. Vulcanized other elastomers are used in vibration isolators, shock absorbers, and along with structures that withstand severe and repeated flexure. They are also used in applications that require good wear resistance. This is due to the unique property of rubber to yield to an abrasive particle, rather than get cut. This is especially useful in the manufacture of tires. Rubbers possess high coefficients of friction when in contact with dry surfaces. This has increased their use in the tire and shoe industry as well as in many mechanical applications. Rubbers are used to line the propeller shaft bearings in ships as the coefficient of friction is very low when wet. Rubbers can be molded under heat and pressure into a variety of intricate shapes during the vulcanization or curing operations. They can be extruded into hoses and gaskets. They can be made to adhere to metals, glass, plastics and fabrics. They are good nonconductors of electrical current and can be used as insulators. Rubbers are attacked by oxygen, sunlight, and ozone and need to be protected by the addition of anti-oxidizing agents. Fluctuations in temperature can cause rubber to lose its elasticity and resilience. Rubber is easily degraded by mineral oils, gasoline, benzene, and other organic solvents and lubricants. They are usually resistant to most inorganic acids and bases and salts, but are affected by strong oxidizing acids like sulfuric and nitric acid, and peroxides.

Synthetic rubbers have been developed to overcome some of the shortcomings of natural rubber. They equal natural rubber in its elasticity and resilience. Some of the commonly used synthetic rubbers are:

Styrene-butadiene rubber: Styrene-butadiene rubber, frequently referred to as Buna-S(Chemische Werke Huels AG) is one of the earlier synthetic rubbers. It is about 70% as resilient as natural rubber has a much lower tensile strength. It also has a poorer tear resistance. It however has good wear and abrasion resistance along with excellent water resistance, which makes it useful in tire applications. It is less expensive than natural rubber.

Acrylonitrile-butadiene rubber: Acrylonitrile-butadiene rubber has low tensile strength when compared to natural rubber and is two-thirds as resilient as natural rubber, but can be compounded to give tensile strengths approaching natural rubber. It loses its resilience as temperature decreases, but its resilience increases as temperature increases.

For this reason, it is used instead of natural rubber in installations where temperatures are much higher than normal room temperature. It is used in gaskets and seals. Another important property of acrylonitrile-butadiene rubber is its resistance to deterioration when exposed to gasoline and oils. It finds use in gasoline hoses, oil-pump seals, and carburetor and fuel-pump diaphragms.

Neoprene: Neoprene(Du Pont), a polymer of chloroprene, has the same resilience and tensile strength as natural rubber. However, it stiffens considerably at lower temperatures and is costlier than natural rubber. It however does not soften at elevated temperatures as does natural rubber. It is more resistant to attack by oxygen, ozone, and sunlight. It is impermeable to air and other gases, and is flame resistant and will not support combustion. It has good resistance to corrosion of chemicals and water. Neoprene is being used in garden hoses, insulation for wire and cable, gasoline-pump hoses, packing rings, motor mountings, and oil seals.

Butyl rubber: Butyl rubber is produced by the copolymerization of isobutylene with small amounts of isoprene. Butyl rubber has tensile strength, resistance to tear, and resilience inferior to natural rubber. It is not resistant to gasoline and oils, and stiffens considerably at low temperatures. However, it is highly resistant to ozone and oxidation and is used when resistance to aging is required. It has excellent dielectric properties, and is resistant to sunlight and all forms of weathering. It is also practically impermeable to air and many gases and is therefore used for products such as inner tubes, tubeless tires, diary hose, and gas masks. It is also resistant to acids and is useful in many applications in the chemical industry.

Silicone rubber: Silicone rubber has a different type of structure that other elastomers. It is not made up of just carbon and hydrogen atoms, but of an arrangement of silicon, oxygen, carbon, and hydrogen atoms. The mechanical properties of silicone rubber including tensile strength, tear and abrasion resistance, resistance to set, and resilience are inferior to that of natural rubber. Its important property is resistance to deterioration at elevated temperatures. Intermittent temperatures as high as 550 °F (288 °C) and continuous temperatures of 450 °F (232 °C) produce negligible change in flexibility and surface hardness of silicone rubber, whereas natural rubber and other rubber like materials would quickly harden or deteriorate. Silicone rubber also has excellent resistance to oxidation, ozone, and aging. It is fairly resistant to oils, and does not deteriorate in gasoline. Because of its high cost (about 20 times that of natural and most synthetic rubbers), it has limited industrial applications.

APPENDIX E

SCREEN CAPTURES FROM THE *DESIGN ADVISOR*

FigureE.1 Welcome screen

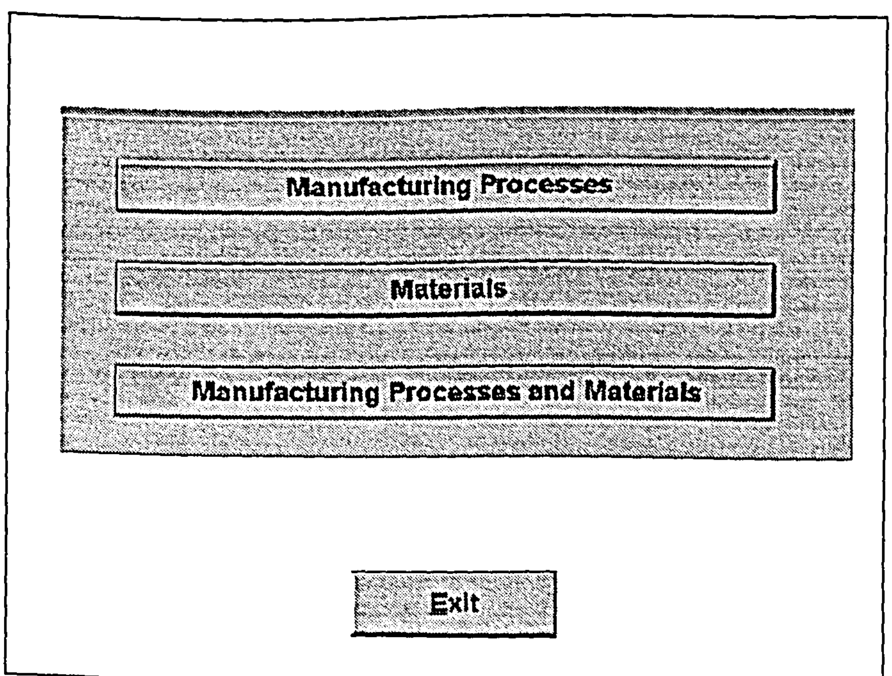


Figure E.2 Selection screen

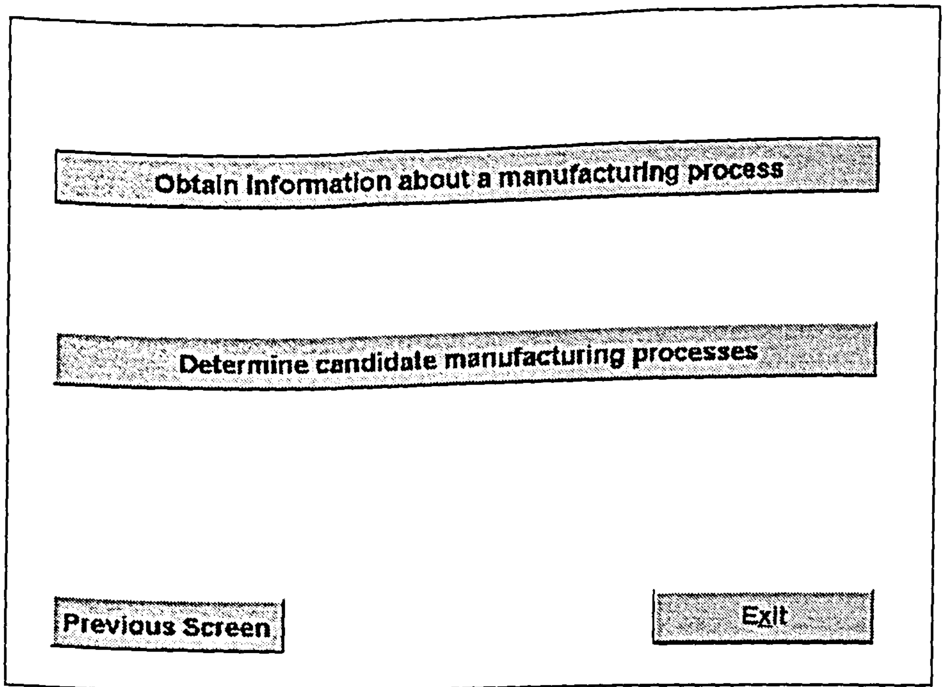


Figure E.3 Search or information on manufacturing processes

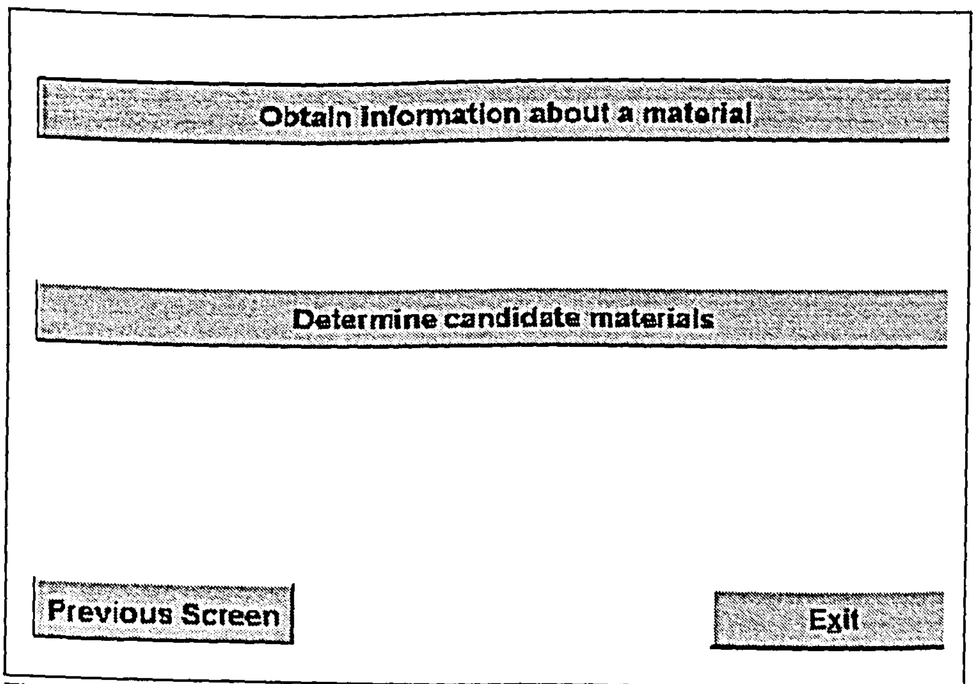


Figure E.4 Search or information on materials

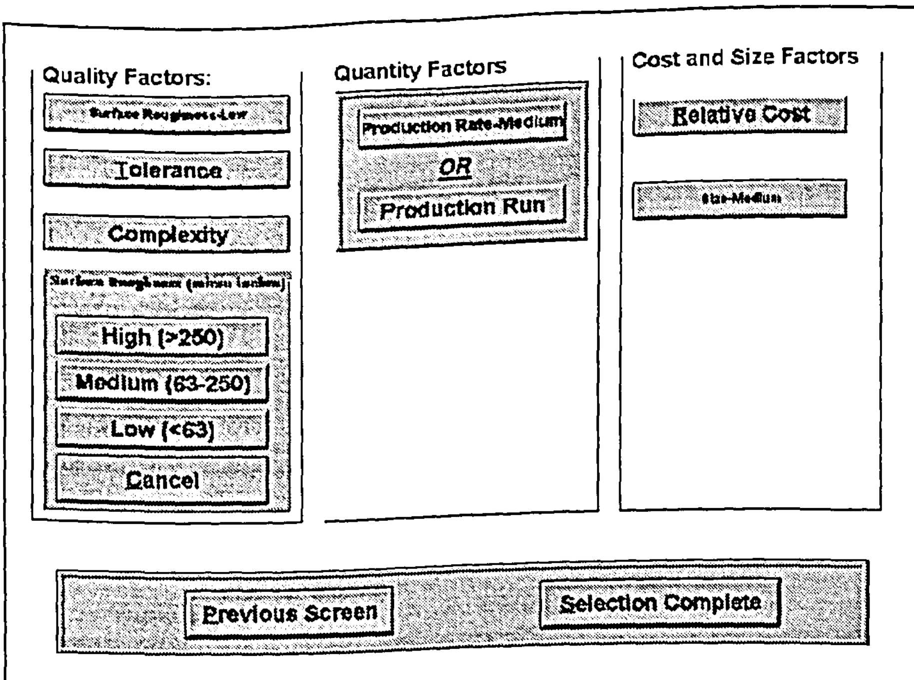


Figure E.5 Selection of manufacturing attributes

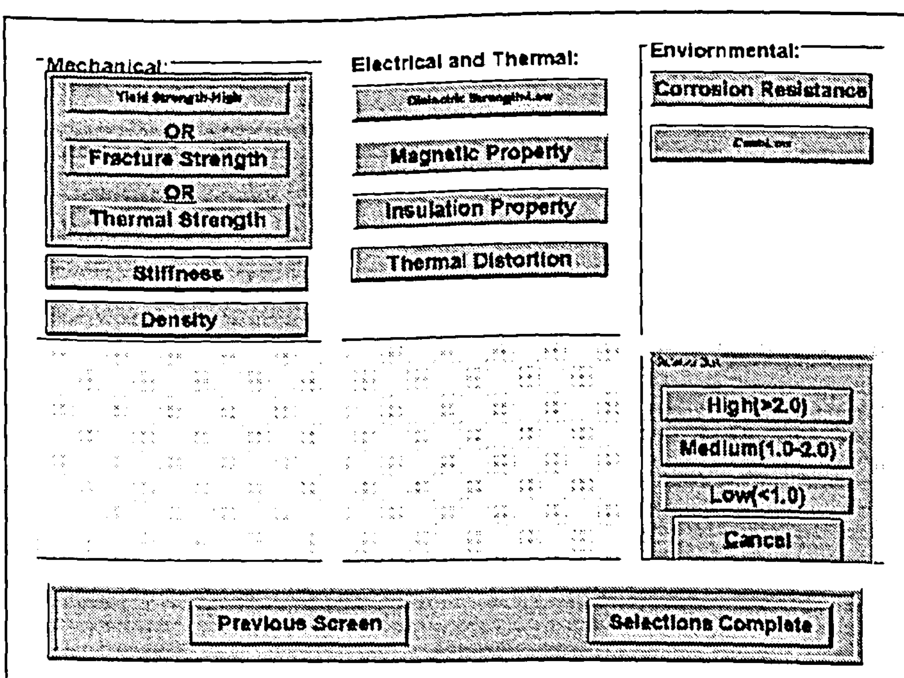


Figure E.6 Selection of material attributes

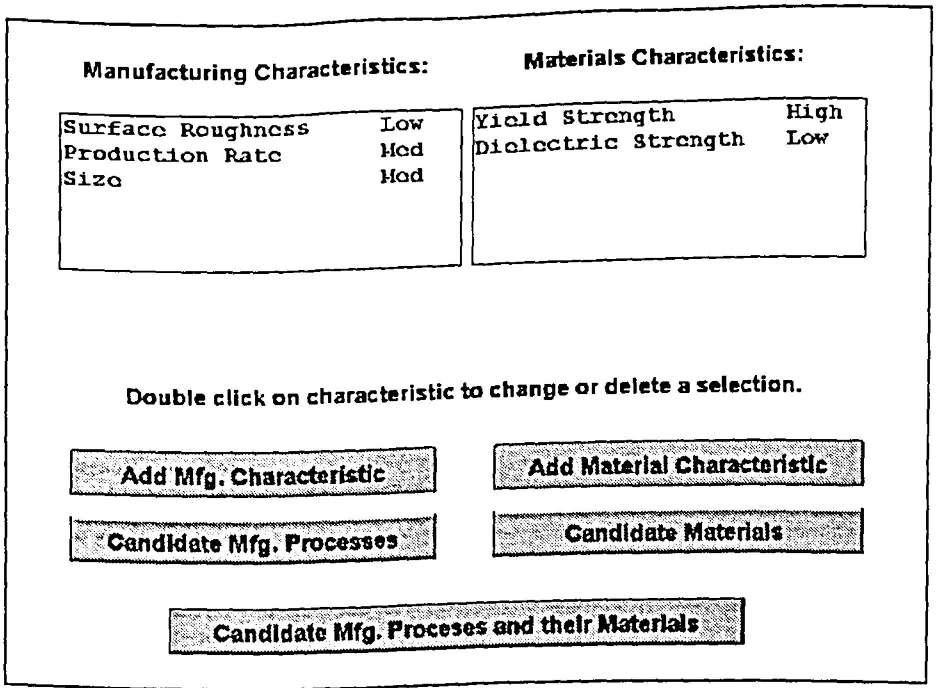


Figure E.7 Summary of manufacturing/material attributes chosen

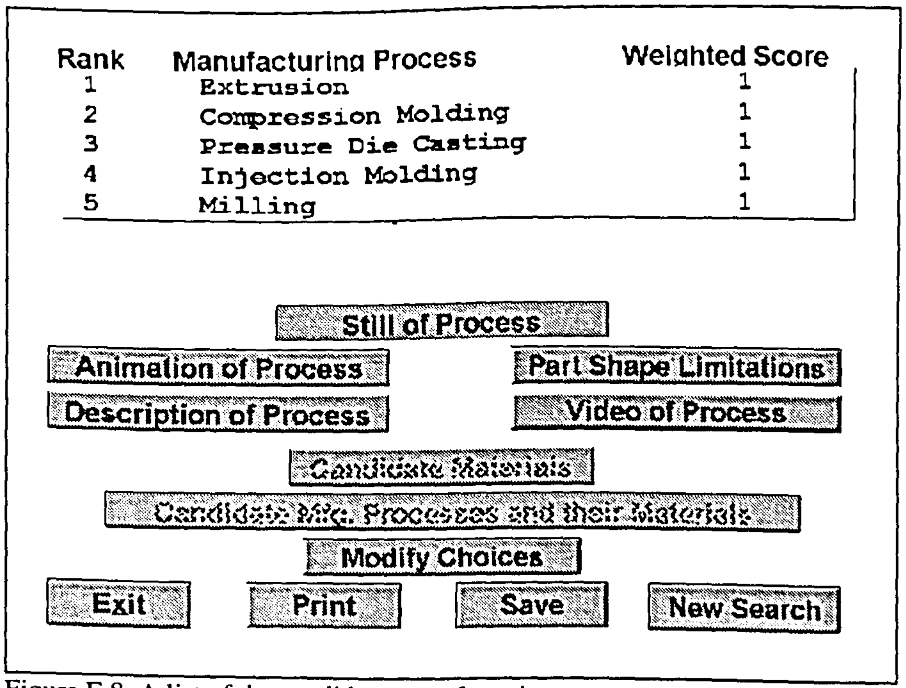


Figure E.8 A list of the candidate manufacturing processes

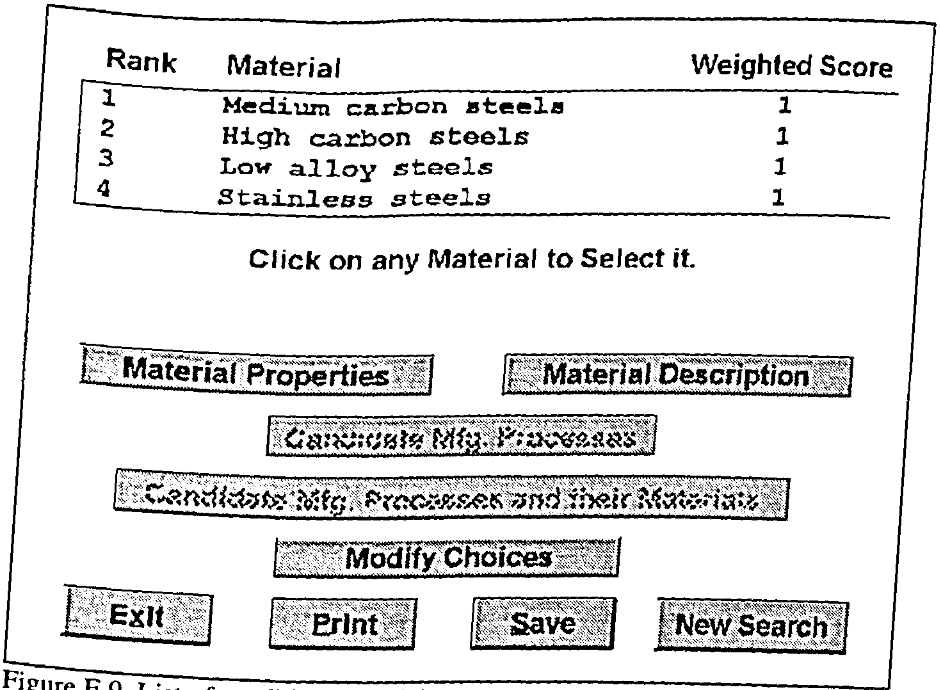


Figure E.9 List of candidate materials

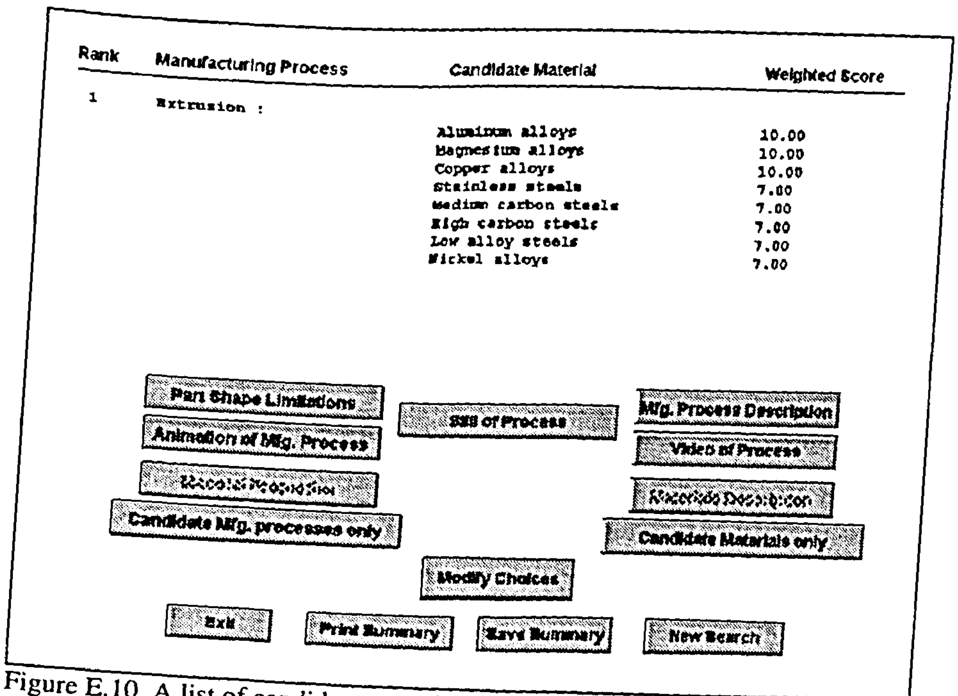


Figure E.10 A list of candidate manufacturing processes and suitable materials

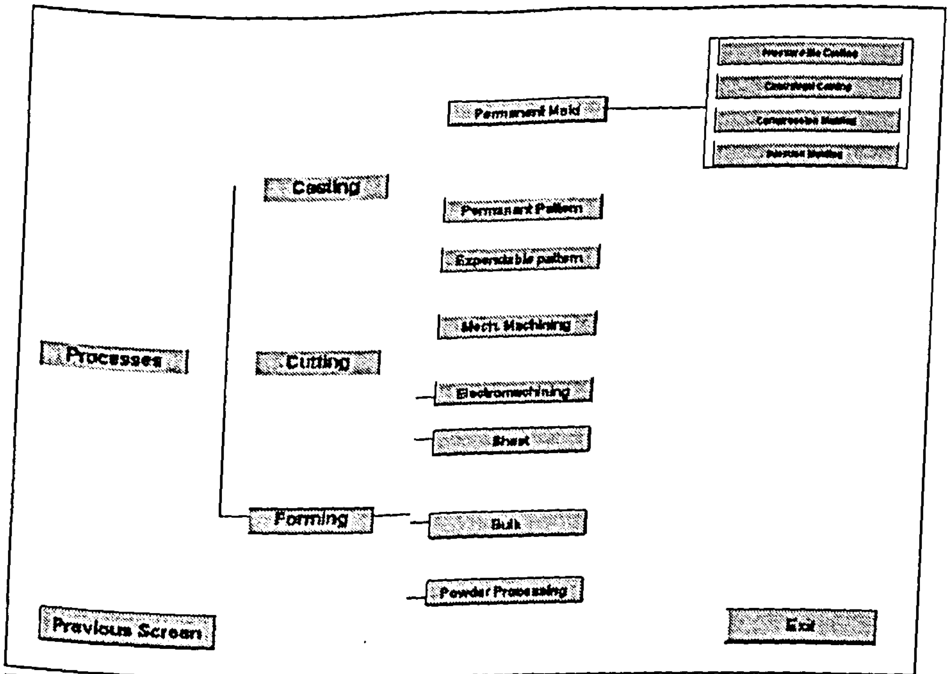


Figure E.11 Clasification of manufacturing processes

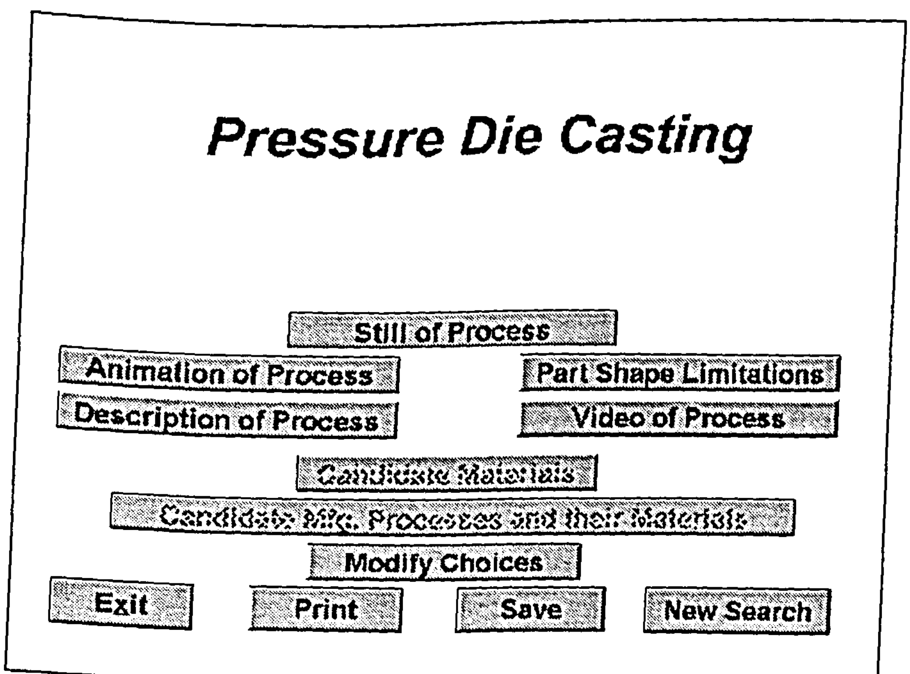


Figure E.12 Information available on manufacturing processes

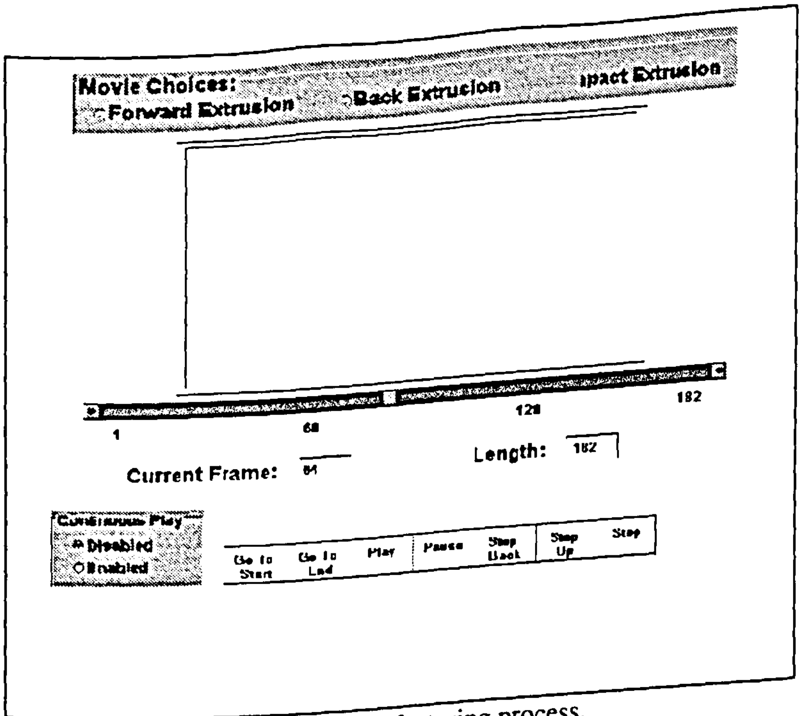


Figure E.13 Animation of a manufacturing process.

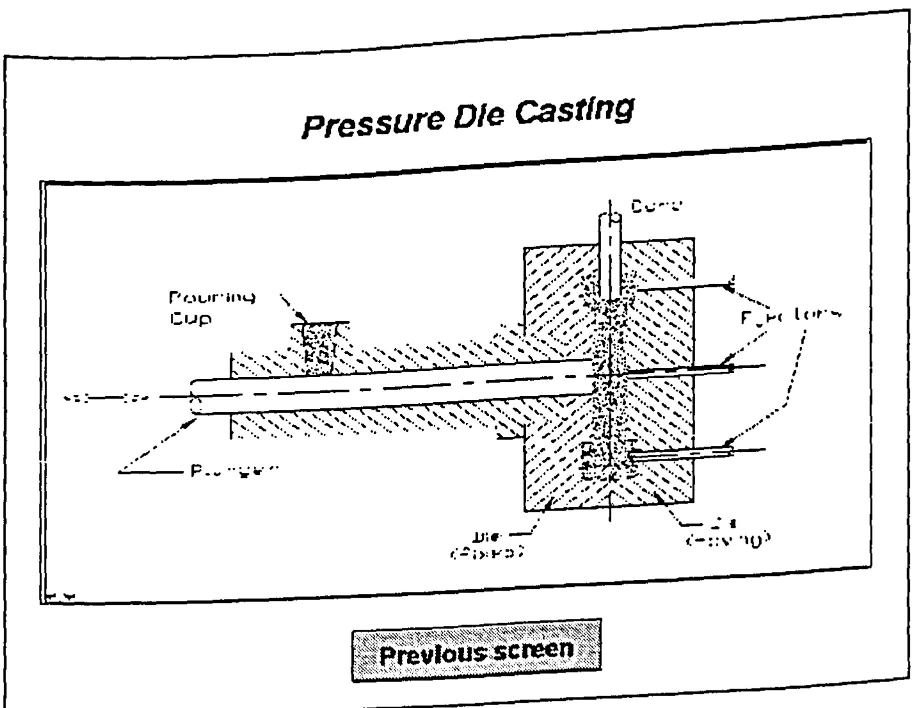


Figure E.14 Still picture of the manufacturing process

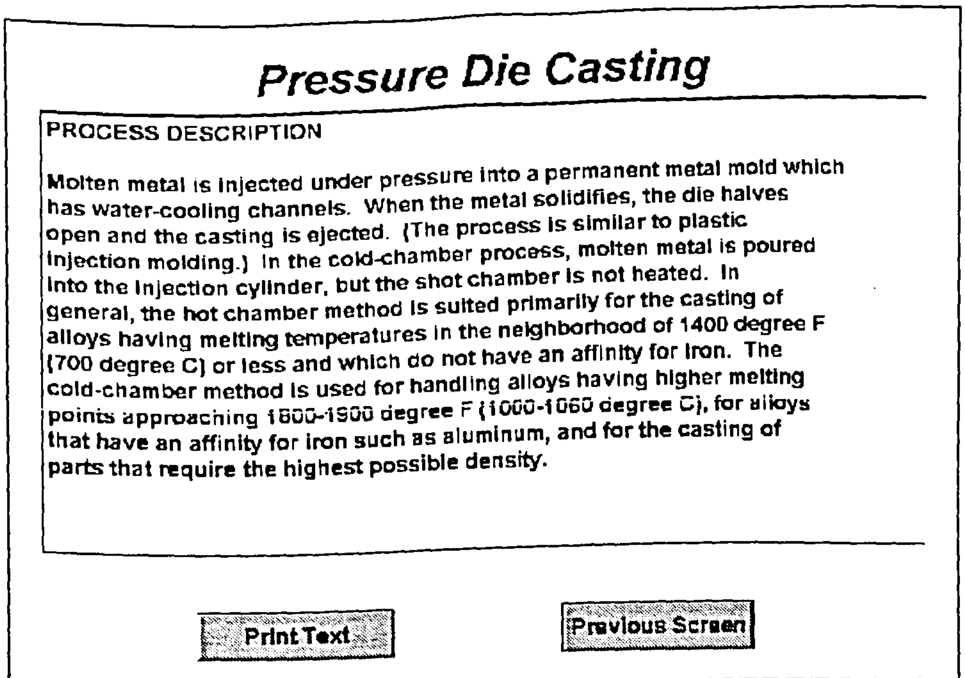


Figure E.15 Text information on a manufacturing process

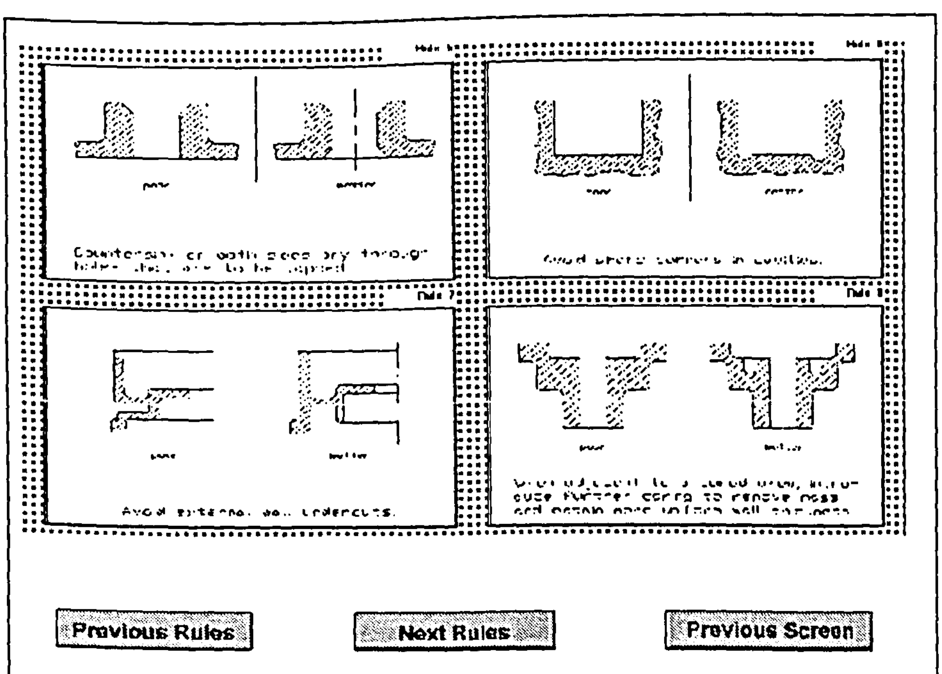


Figure E.16 Design rule pictures for a manufacturing process

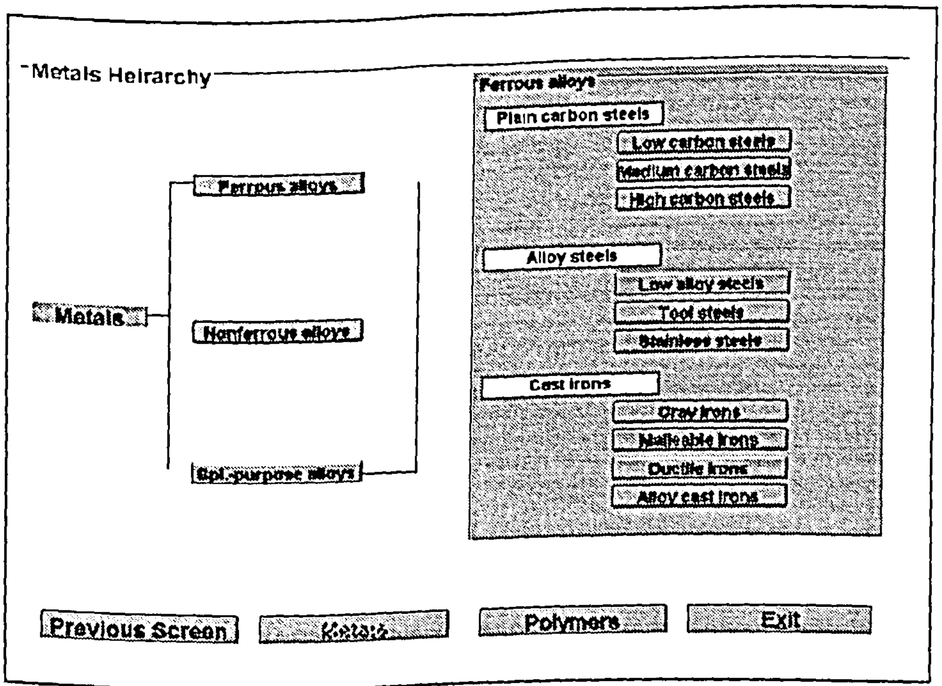


Figure E.17 Classification of materials [metals]

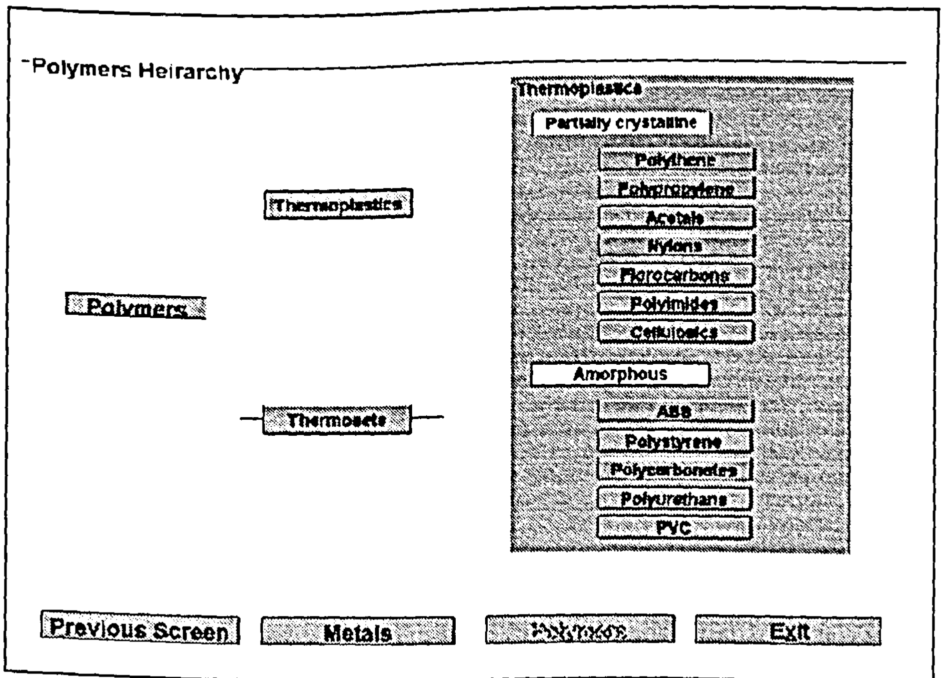


Figure E.18 Clasification of materials [plastics]

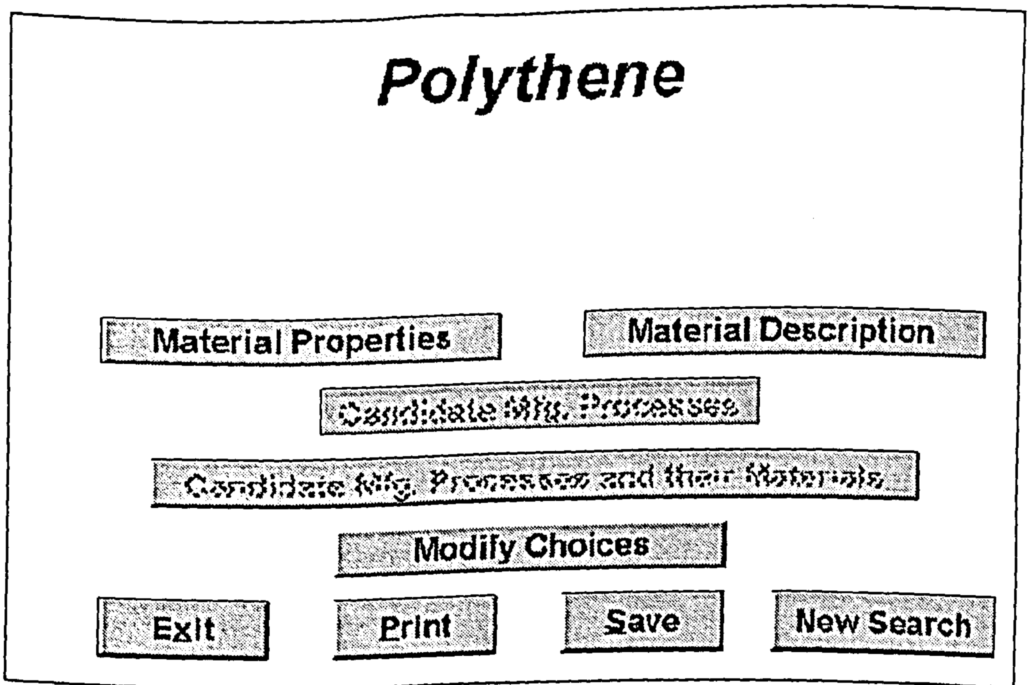


Figure E.19 Information on materials

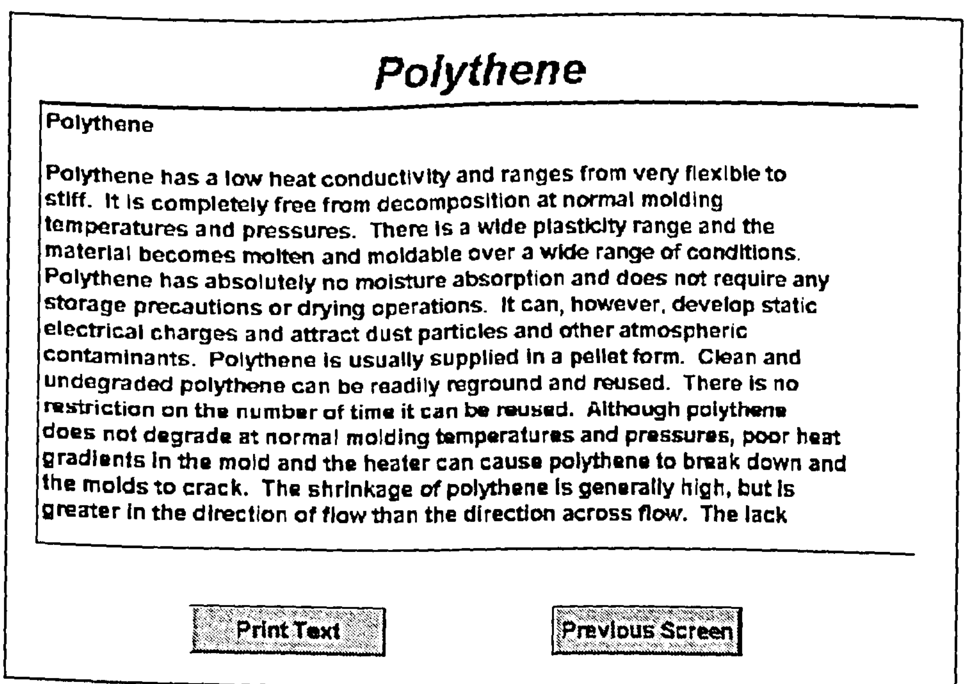


Figure E.20 Text information on a material

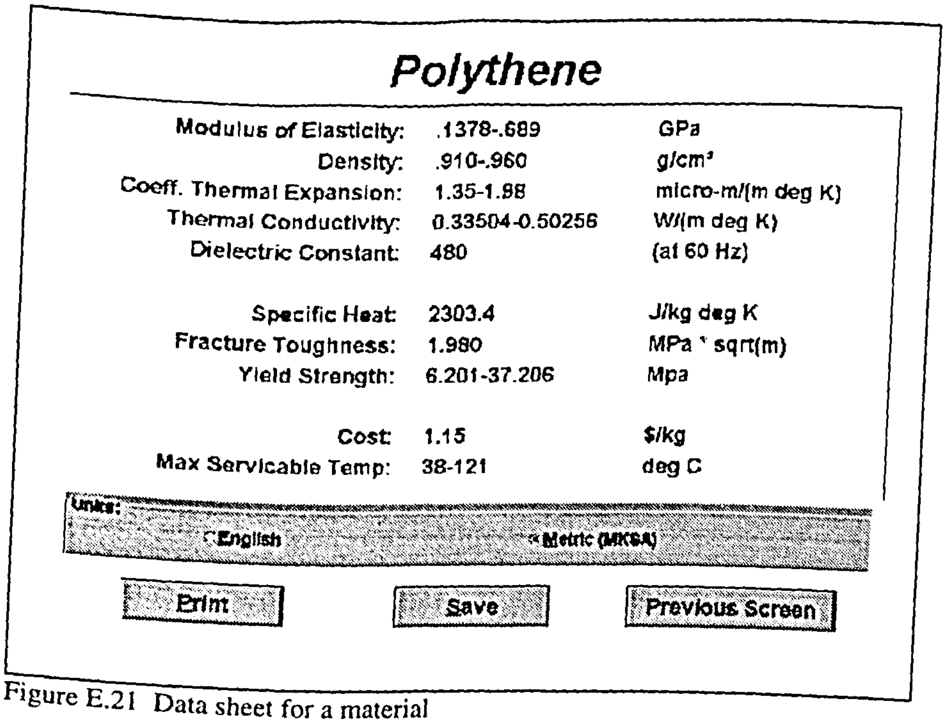


Figure E.21 Data sheet for a material

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