The relationship between Materials selection and Materials Processing

There is no profit in selecting a material which offers ideal properties for the job in hand only to find that it cannot be manufactured economically into the required form.

1.1 The purpose of materials processing

Materials processing has three principal aims. These are the achievement of
(1) shape and dimensions,
(2) properties , and
(3) finish (this last in the sense of ready to use quality).

1- shape and dimensions

These are obtained by three basic methods
(a)rheological (flow)processes,
(b)fabrication (the assembly) of readymade constituent parts by joining, and
(c)machining.

a)-Flow processing

This method can be used to shape liquids, fluids and solids: it includes
- the liquid casting of metals,
-injection moulding of plastics,
-slip casting of ceramics,
-mechanical working of metals and the densification of powder metallurgy compacts.

b)-Fabrication

This is accomplished by mechanical, metallurgical or chemical methods of joining.

*Mechanical methods, include

riveting and bolting and other diverse methods of clipping and fixing. These methods are *widely* used, sometimes because of the need for a demountable joint, or because of the simplicity and convenience of assembly.

*Metallurgical techniques embrace welding, brazing and soldering and each has a range of applications in which it is the preferred method of permanent assembly: thus, welding for heavy engineering, soldering for electrical circuits.

*Chemical methods involve the use of adhesives, glues or cements for timber and metallic materials, adhesion is well established method of fabrication and for most joint pairs within these groups of materials it is possible to specify a suitable adhesive.

The fabrication of large scale metallic structures, for which welding is the usual method of joining, presents problems in relation to dimensional tolerance.

There are obstacles to the use of adhesives for the assembly of large structures: if joints of good integrity are to be assured the precision of dimensional fit and surface preparation must be of very high quality.

c)-Machining

Machining represents the failure of the processes that have preceded it. Expensive in terms of energy and labour, wasteful of basic resources and requiring a good deal of costly capital equipment, it retains its major position within production engineering only because of its ability to make up for the shortcomings of other processes.

Naturally enough, reduction in machining by other means of near net-shape forming, with improved surface finishes, is constantly sought.

Reynolds' has given an analysis for the costs of machining a bought-in blank or semi-finished product. Suppose the unit cost and weight of the blank are CB and WB' respectively, whilst the corresponding quantities for the finished part are CF and WF. Let the cost of producing unit weight of swarf be CM' This will be made up of the total machining cost less the re-sale value of the swarf produced. Then

$$CF\ WF = CB\ WB + CM(WB - WF)$$

If the yield of the process, WF / WB' is denoted by y then

$$C_f = \frac{C_B}{y} + C_M \frac{(1-y)}{y}$$

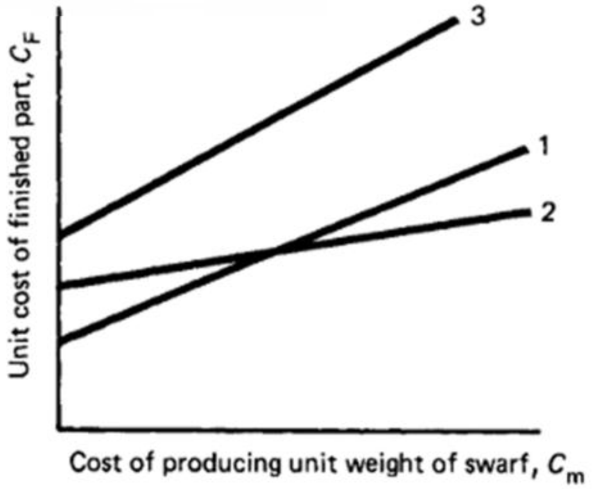

Figure 13.1 Cost relationships for machining processes.

In the first case the cost of the blank is low but the machining yield is also low. In the second case the reverse applies, with the unit cost of the preformed blank generally being lower, the larger the scale of production. If there is to be a real choice between two such processes then the two curves must intersect, and this requires that the intercept of curve 1 be less, and the slope greater, than the corresponding values for curve 2, i.e.

$$\frac{C_{B1}}{y_1} < \frac{C_{B2}}{y_2} \quad \text{and} \quad \frac{1-y_1}{y_1} > \frac{1-y_2}{y_2}$$

This means that CB, > CB, and Y2 > YI' If these conditions are not met, as between curve 3 and either of the others, there is no intersection and therefore no choice, since process 3 will always be the more expensive. Which of processes 1 and

2 is to be preferred depends upon a number of factors. Consider, for example, a steel part which may be produced with equally satisfactory properties by automatic machining from plain bar stock (process 1), or finish machining of steel forgings (process 2). If we assume initially that C81' CB2, YI and Y2 are fixed, then process 1 would be preferred to process 2 if it happens that

the real machining costs are smaller than the value given by the intersection of curves 1 and 2. One factor which greatly influences machining costs is the machinability of the material. This can be influenced by the metallurgist, since if it is desired to favour process 1, the purchase of free- machining steel bar stock containing sulphides greatly reduces machining costs (although at the expense of some degradation of mechanical properties as compared with the forgings).

2-Properties

The properties of an engineering part derive mainly from the basic nature of the material of which it is made, but where metallic materials are concerned, properties can generally be greatly modified during the successive stages of a manu- facturing process. This is impossible with unprocessed natural materials such as timber and stone, but the approach of modifying structure by processing can be applied to products where the basic ingredient is wood or mineral (e.g. chip- board, plywood, reconstituted stone and cement products). It is also an approach which is increasingly applied to non-metallic manufactured materials, i.e. ceramics, glasses and plastics.

The ability to control properties of a part during manufacture often allows these to be better matched to application than might otherwise be the case, especially in respect of the magnitude and directionality of mechanical properties. A shaped metallic casting is a primary product where only the solidification process is available to modify the potential properties of the basic material (control of solidification, however, must not be under- rated since the use of chills and denseners to control feeding of shrinkage, directional solidification, and grain refiners, etc. can profoundly modify the properties of castings). On the other hand, the separate processes that culminate in a metal sheet will have included solidification in an ingot, reheating, hot-rolling, cold-rolling and annealing in a complex sequence of operations, at every stage of which its properties will have been manipulated to suit its final use, whether this be for a transformer lamination, an aeroplane wing, a deep-drawn can or a simple machine cover. In contrast, once the melt for making an injection- moulded plastics component has been prepared there is less in the subsequent manufacturing procedure that can significantly modify its properties.

Such limitation can be accepted because, as Beeley? has pointed out, there are two aspects to the quality of a manufactured artefact, one concerned with the quality of the material of which it is made, the other with the quality of the artefact as an engineering component, deter- mined by the integrity of its shape, dimensions and finish. It is the second of these two aspects which is often the more important and which must take precedence if there is any conflict between them.

3-Finish

This includes engineering tolerances, surface quality, surface protection and appearance.

In so far as it is essential to the proper mechanical functioning of a component, finish is a property that can be precisely specified, for example, in terms of standard limits and fits and parameters of surface topography (Talysurf - centre-line average). Desirable levels of surface protection and appearance are a little more difficult to quantify and the choice between, say, galvanized or cadmium-plated steel and ano- dized aluminium or chromium-plated plastics may present problems, notwithstanding the eas- ily-determined variations in cost.

Surface processing purely for appearance is entirely a subjective matter, and decisions can hardly be taken without the benefit of market research. However, for light reflectors, and other applications requiring highly finished surfaces, quality can be assessed quantitatively in terms of the relative proportions of specular and diffused reflection, using standardized methods of measurement.

1.2 The background to process selection

Before choosing a process for the manufacture of a given article, apart from taking into account the material selection, it is necessary to know

(1) How many are required,
(2) The size and weight per piece,
(3) The geometrical complexity,
(4) The required dimensional tolerances and
(5) The desired surface finish.

Effect of numbers required

Except for a prototype, it is rare to manufacture only one of a given part: usually larger numbers are required, varying from, say, ten to hundreds of thousands. A large production reduces the unit cost, i.e. the cost of each individual piece, since larger numbers permit the use of more complex machinery and more advanced manufacturing methods. However, coping with a large production demands more highly developed techniques of inspection and quality control, not only of manufacturing methods throughout the factory but also of incoming material. To achieve overall benefit, the additional costs thereby incurred must be smaller than the savings accomplished by high-volume production.

The effect of production numbers on costs can be analyzed as follows:

The total cost, P, of a batch of N pieces can be expressed as

$$P = T + xN \tag{1.1}$$

in which T is the cost of tools and equipment and x represents the costs associated with each individual piece.

T varies very greatly from one process to another. At one extreme the cost of a wooden pattern and moulding box for a metal casting might be less than £100. At the other extreme the cost of tools for producing an injection moulded thermoplastic article could exceed £20,000. x is made up of several components. These are M, the unit material cost: F, the unit cost of finishing and rectification: L, the proportion of labour and factory overhead costs borne by each piece, expressed as cost per unit time; and R, the rate at which the pieces are produced. Expanding equation (1.1):

$$P = T + N\left(M + F + \frac{L}{R}\right) \tag{1.2}$$

Comparing one process with another, M(constant). L is not constant (staff for inspection, quality control and maintenance). R(productivity) and should increase with more advanced machinery.

The effect of installing more efficient processing machinery should be to reduce the value of *x* in equation (1.1). However, *T* will simultaneously increase and this means, referring to Figure 13.2, that *x* must decrease by an amount sufficient to make the curves intersect at a useful value of N.

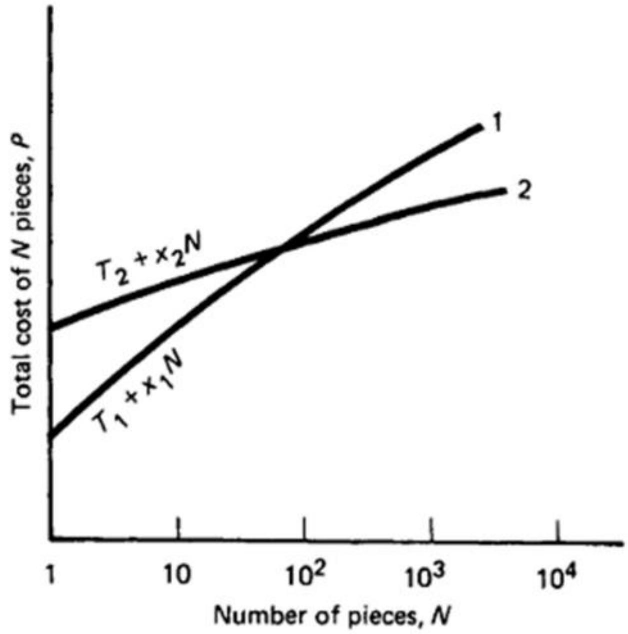

Figure 13.2 Effect of production quantity on manufacturing costs.

The point of intersection in Figure 13.2 gives the minimum batch size which makes it worthwhile to replace process 1 with process 2. From equation (13.2) this critical number is given by

$$N_c = \frac{T_2 - T_1}{(F_1 - F_2) + L\left[\left(1/R_1\right) - \left(1/R_2\right)\right]} \qquad (1.3)$$

To allow maximum utilization of the more advanced process, *N;* should be as small as possible and for this to be so the latter process should produce pieces that require less finishing and rectification and at a faster rate so that any increase in **L** is more than offset by larger **R**. The effect of production numbers on tooling costs is seen more clearly if equation (1.2) is rewritten to give unit cost:

$$\frac{P}{N} = \frac{T}{N} + \left(M + F + \frac{L}{R}\right) \qquad (1.3)$$

If the injection-moulding tools referred to earlier were used to make a batch of 100 pieces, then it is inevitable that the cost of each piece must exceed £200 - such expensive tools could not be justified for such a small number. But if N is large enough there is no limit to the permissible expenditure on tools because however large T is, T/N becomes negligible. Sufficiently large numbers could even permit the building of a new factory. For low volume production tooling, it may be possible to utilize 'soft-tooling' methods, facilitated by the application of rapid prototyping techniques. Among the manufacturing methods for soft-tooling are metal spray tools, cast resin or metal tools and electro discharge machined (EDM) electrodes for tools. For plastics, vacuum forming, blow moulding and resin injection moulding can utilize soft-tooling. For metal sheet forming, fluid cell and rubber pad pressing and superplastic forming can take advantage of low-cost soft-tooling.

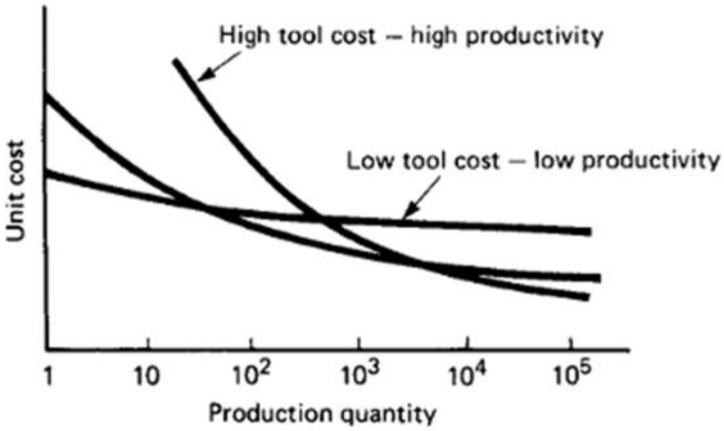

Figure 13.3 Effect of production quantity on unit cost for different processes.

Figure 13.3 shows unit costs as a function of production quantity for three processes of increasing' tool costs.

Effect of size and weight

Each process and material has its own characteristic limits of size. The upper limit on size is most restrictive in those processes which require closed metal moulds, such as shell **moulding, diecasting**, and **closed die forging**. On the other hand, sand castings are limited in size only by the available supply of liquid metal, although very large castings must be skilfully designed, first, to persuade liquid metal to flow for long distances through the mould cavity and, second, to avoid unsatisfactory mechanical properties in thick sections, especially if these are joined by thinner sections. According to [ackson ' steel castings can be produced in weights up to 250 tonnes but in most jobbing foundries a 25 tonne casting would generally be described as large. The largest forgings in regular production are steel alternator rotors, the bodies for which may attain 200 tonnes, although the low yield characteristic of these products would necessitate an as-cast ingot weight in excess of 300 tonnes. In airframes, a forging would be regarded as large if it weighed more than 2 tonnes: most aircraft forgings weigh between 25 and 250 kg (50-500 lb).

At the other extreme, it is difficult to produce forgings smaller than 100 g or so, whereas casting processes, e.g. pressure diecasting, can produce pieces three orders of magnitude smaller than this. Technically, this is because metals flow into small channels much more readily when they are liquid than when they are solid, but economically it is facilitated by the fact that all casting processes can employ multi- cavity moulds - it is possible, for example, to obtain a hundred or so castings from a single investment-casting mould (lost wax process).

Stampings and pressings, which involve very little material flow, can be made in a wide range of component sizes.

Complexity of shape

Factors which contribute to complexity are:
(1) minimum section thickness,
(2) presence of undercuts,
(3) presence of internal hollows.

Dimensional tolerances

Different manufacturing processes vary widely in the dimensional tolerances of which they are capable. Reynolds" has presented evidence that in practice designers tend to use certain constant values of tolerances, such as 0.010 in, 0.020 in, etc., regardless of the overall magnitude of the dimensions to which they apply. He discusses the International Standards Organization proposal that the tolerance applied to any dimension should be related to the magnitude of that dimension; because the larger a dimension is, the more difficult it is to achieve a given fixed tolerance. ISO propose empirical relationships of the following type:

$$\text{Tolerance (microns)} = 0.45X^{1/3} + 0.001X$$

where X is the nominal dimension in millimetres. This defines Grade 1 of the ISO tolerance grades (designated IT).

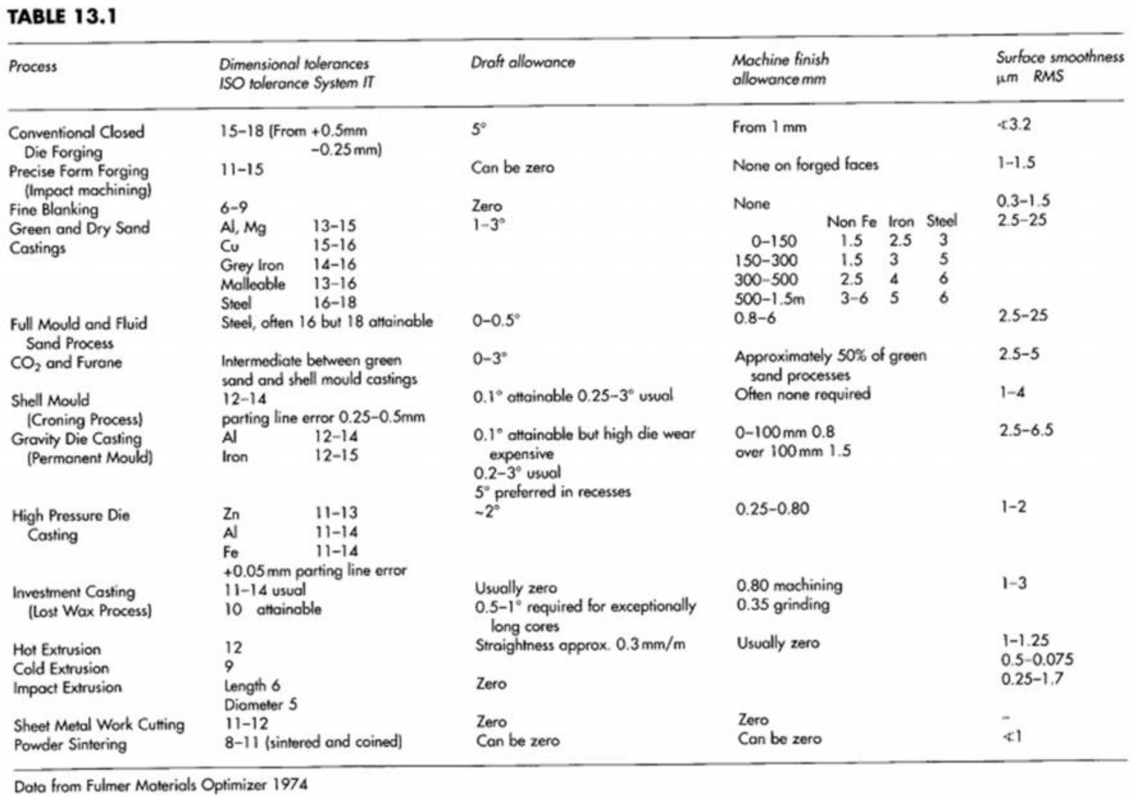

TABLE 13.1

Process	*Dimensional tolerances ISO tolerance System IT*	*Draft allowance*	*Machine finish allowance mm*	*Surface smoothness µm RMS*
Conventional Closed Die Forging	15–18 (From +0.5mm −0.25 mm)	5°	From 1 mm	<3.2
Precise Form Forging (Impact machining)	11–15	Can be zero	None on forged faces	1–1.5
Fine Blanking	6–9	Zero	None	0.3–1.5
Green and Dry Sand Castings	Al, Mg 13–15 Cu 15–16 Grey Iron 14–16 Malleable 13–16 Steel 16–18	1–3°	Non Fe Iron Steel 0–150 1.5 2.5 3 150–300 1.5 3 5 300–500 2.5 4 6 500–1.5m 3–6 5 6	2.5–25
Full Mould and Fluid Sand Process	Steel, often 16 but 18 attainable	0–0.5°	0.8–6	2.5–25
CO_2 and Furane	Intermediate between green sand and shell mould castings	0–3°	Approximately 50% of green sand processes	2.5–5
Shell Mould (Croning Process)	12–14 parting line error 0.25–0.5mm	0.1° attainable 0.25–3° usual	Often none required	1–4
Gravity Die Casting (Permanent Mould)	Al 12–14 Iron 12–15	0.1° attainable but high die wear expensive 0.2–3° usual 5° preferred in recesses	0–100 mm 0.8 over 100 mm 1.5	2.5–6.5
High Pressure Die Casting	Zn 11–13 Al 11–14 Fe 11–14 +0.05 mm parting line error	~2°	0.25–0.80	1–2
Investment Casting (Lost Wax Process)	11–14 usual 10 attainable	Usually zero 0.5–1° required for exceptionally long cores	0.80 machining 0.35 grinding	1–3
Hot Extrusion	12	Straightness approx. 0.3 mm/m	Usually zero	1–1.25
Cold Extrusion	9			0.5–0.075
Impact Extrusion	Length 6 Diameter 5	Zero		0.25–1.7
Sheet Metal Work Cutting	11–12	Zero	Zero	–
Powder Sintering	8–11 (sintered and coined)	Can be zero	Can be zero	<1

Data from Fulmer Materials Optimizer 1974

In successive tolerance grades, the tolerances increase by multiples of $10^{1/5}$ that is, they increase by an order of magnitude for every five tolerance grades. Thus, if the characteristic dimension of a casting is 40 mm then tolerance grade IT 1 corresponds to a tolerance of 1.58 urn. The best casting process in this respect is pressure diecasting which, at its best, meets tolerance grade IT 11: this for the 40 mm casting gives tolerances of 158 urn, The same casting, manufactured in steel from a green sand mould, could, at its worst, require tolerances according to tolerance grade IT 18, i.e. 4 mm. Other processes produce results that are intermediate between these two extremes (see Table 13.1). It is seen that the lower the IT number the better is the quality of tolerances, and that hardly any process is capable of attaining a tolerance grade as good as IT 9.

Surface finish

Surface finish, or the degree of approach to perfect smoothness of a surface, is generally expressed as some sort of average measurement of the surface profile about a central mean, either centre-line-average (CLA) or root-mean-square (RMS). Once again, pressure die casting and sand casting offer the extremes of results, with possible figures of 1 and 25 urn RMS, respectively. Some alloys are much worse than others: sand-cast phosphor-bronze produces especially rough castings. Poor surfaces due to metal- mould reaction are obtained from several combi- nations of metal and mould.

1.3 The casting of metals and alloys

As a method of shaping, casting has two great advantages: almost any shape can be produced (although cost increases with increasing complexity) and there are many available processes, covering a wide range of high and low capitalization, with continued development into new techniques (e.g. rheo-casting and squeeze casting).

Although castings in small batches can be obtained economically with quite modest equipment, high-volume production calls for a good deal of mechanization: the tooling and associated equipment required for a consumer- durable component could cost tens of thousands of pounds sterling.

The score or more of different casting processes from which it is now possible to choose differ mainly in the material of which the mould is made and the size and number of castings which can economically be produced.

Three factors influence the choice of mould material:

(1) cost,

(2) fidelity of shape and dimensions, and

(3) thermal properties.

Cost

Where many identical castings are required, it is sensible to reduce unit cost by employing a mould which can be used many times. The initial cost will be greater, but provided this can be spread over a sufficient number of castings then, as discussed previously, there will be a reduction in total cost. Sand moulds can be used only once, and this is true also of plaster moulds. Some ceramic moulds can be used a few times if the casting is of simple design but, of course, the longest runs are obtained from dies of steel or heat-resisting nickel alloys. Unfortunately there are clear economic disadvantages in the use of metal dies; the lead time for die manufacture is long and cost is high. The cheapest metal moulds are those intended for manual operation (permanent moulds or gravity dies), but the production rate with such dies is generally low and can be substantially lower than when filling sand moulds. In contrast, the dies used for high- pressure die-casting are extremely expensive since they are pressure-filled from complex machines and contain mechanisms for with- drawing cores, opening the mould and ejecting the castings at high speed. The cost of such a die must be spread over many thousands of castings. The working life of a re-usable mould is the number of times it can be used before deterioration of its working face causes unacceptable surface blemishes on the castings.