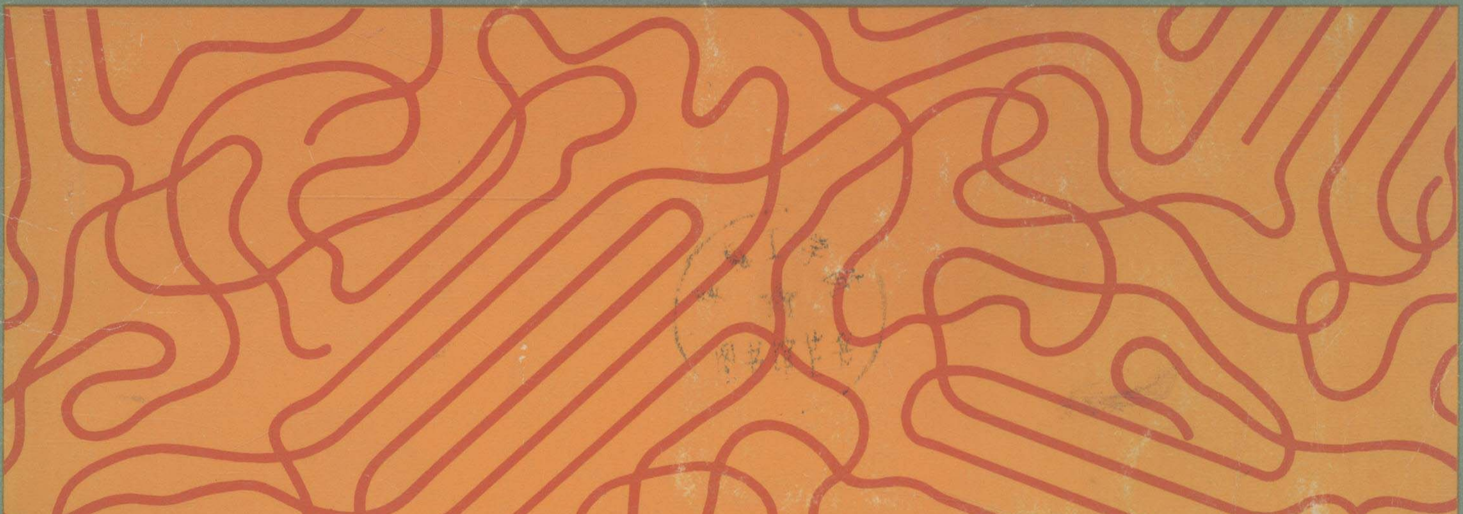
Materials 24

Engineering Design Guides

PLASTICS MOULDINGS

J H Postans



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Introduction

The principal method by which polymer or plastics material is converted into useful products is by moulding, usually under heat and pressure, in a hollow mould or die. The material takes the shape of the mould, from which it is then removed. The relationship between the final product and its mould is of critical importance, both dimensionally and with regard to material properties.

Any successful design requires comprehensive information on a wide range of parameters. This Engineering Design Guide adopts a practical approach in considering those parameters that are of primary importance in the design of plastics mouldings. Because of their complementary nature, thermoplastic and thermosetting materials are dealt with jointly.

Although processing techniques and their effects on the physical and chemical structure of the product vary, all the materials in the range under consideration soften under heat and flow under pressure. It is important to bear in mind that any one class of material may consist of between six and sixty variations accounted for by changes in molecular weight, by chemical combination with other materials, or by the use of fillers. Examples of these variations include modifiers, lubricants, and copolymers (such as ethylene–propylene copolymer).

It must be emphasized that good design cannot result from a knowledge of material parameters only. The effect of processing on the material is extremely important, and all aspects of the design process must be covered including the technical characteristics of the materials and the correct design and temperature control of machines and tools.

Other related titles in the Engineering Design Guide series are *The engineering properties of plastics* and *The selection and use of thermoplastics*.

Preliminary considerations

The successful application of plastics materials depends on the correct choice of material, and the optimization of its properties to ensure a satisfactory service life, at a price which is competitive.

The designer must have a thorough knowledge of materials and processes in order to ensure a correct choice of material, the procedure for which is as follows:

1. The finished product must be accurately specified in terms of strength, stability, and resistance to different environments.
2. Those groups of plastics which are not suitable for the product under review are eliminated.
3. The remaining groups of materials which offer potential must then be examined. Of equal significance to the published properties are their weaknesses, which may now be used as the basis for further discrimination. Such weaknesses may be found in all grades of a particular group of materials, or they may be significant to the processing characteristics of only certain grades of a material. Decisions that can be made on this basis may be influenced by the knowledge that, for example, a close-tolerance part cannot be produced successfully to a consistent standard from a high-shrinkage material; a proposed method of processing would have some effect on the finished product (for example, structure orientation may be altered), or a particular material may not be suitable for secondary operations (such as assembly).
4. It must be established that the product requirements are compatible with the potential of the chosen material, leading to optimum use of its properties.

The designer should note that data presented in the form of general properties of plastics materials are of necessity generally obtained from laboratory testing. However since information is not always readily available on the change in these properties after ageing or on exposure to a specific environment, relating the result on a simple test-piece to in-service conditions is not easy. Thus further tests may have to be carried out to ensure that the material is capable of meeting certain particular requirements.

The designer should bear in mind the following examples of discrepancies between quoted properties obtained under test conditions and in-service behaviour.

1. A piece of material which is immersed in acid for a specified time and then washed and tested for comparison with its value before immersion may be found to be satisfactory; however, in practice, where the material may be subjected to an acid spray at infrequent intervals, it may fail very rapidly.
2. A material may have excellent resistance to a solvent under test conditions. However, if a finish that necessitates mechanical polishing is specified, surface crazing, which results in notching and initiation of mechanical failure, may occur on exposure to solvent.
3. The impact resistance of long-fibre-filled thermosetting materials in particular is much greater than that of the wood-filled material. However, since failure may occur as a result of a significant crack as easily as it can from complete disintegration, the reported resistance of the long-fibre-filled material is in question. It may crack at a load under which another more easily moulded material breaks; thus both materials will fail to meet the requirements of the product.
4. Certain materials may withstand single-impact blows better than do others. However, where such impact is repetitive, materials may demonstrate differing ability to resist in a satisfactory manner.

Having selected a material and its particular grade for a specific application the designer may then determine component thickness and other design features related to flow and shrinkage characteristics of the material, and consider any other relevant items (for example, notch sensitivity).

Product design objective

The design of a product should be such that it ensures a satisfactory service life at a competitive price. The design objectives for each product will be based on strength in relation to environment. For example, the service life of a motor vehicle might depend on the annual mileage, and different design objectives would be necessary according to the duty of the vehicle. In the case of building products, the service life required may be 20 years in the humidity of a bathroom, or even longer when fitted externally as face decoration. Parts used in structural applications and pipework for corrosive fluids involve other relevant physical quantities, and the life expectancy of such parts must be accurately forecast in order that a replacement programme may be planned, and the system as a whole may be made fail-safe.

The determination of an acceptable service life demands a knowledge of the product and the ability to anticipate any change in conditions that may arise. The fact that articles must be produced at competitive prices does not in any degree lessen the responsibility of the manufacturer to supply goods that will give satisfactory service.

The material selected for an application will generally be the one which combines the lowest cost with the best processing capability and the required degree of stability and performance in that application.

Material properties

Stiffness and strength

Temperature and time are two factors which affect the deformational characteristics of plastics, usually described in terms of 'creep'. Creep is defined as deformation of a material under load over a period of time. In this connection one of the most important parameters for plastics is the operating ambient temperature of the material, since relative creep increases with increase in temperature. Most creep data are obtained under constant load, which is usually tensile; thus as creep increases the stress increases by reason of the corresponding reduction in area. If during a creep test a component is loaded for a period of time, fracture can occur following an initial period of creep. This is known as creep rupture. It has been found that the lower the stress at which creep rupture occurs, the longer the time taken to fracture. Creep rupture is extremely important and has a significant effect on, for example (1) the design of plastics water-pipe which is subjected to internal pressure for long periods of time; (2) covers which, although possibly purely decorative, are manufactured for interference fits on metal bases under constant load; and (3) significant loads which may be encountered in assembly either from metal screws or rivets fastened on to a plastics component or from plastics fastening devices. Useful creep data are given in Table A1.1, Appendix 1. Further information can be obtained in literature supplied by the Rubber and Plastics Research Association of Great Britain.

The following are significant factors affecting the stiffness and strength of plastics materials.

1. *Temperature*. The stiffness of many plastics is reduced very significantly by an increase in temperature. Table A1.1 gives values of tensile modulus at room temperature and at 115°C.

2. *Time*. A plastics component will creep under constant load, that is the deformation will increase continuously over the period of time that the load is applied. Table A1.1 gives the value of the tensile modulus after a short time under load and also after 500 h and 1500 h under load.

3. *Strain limit*. In the absence of further information the maximum permissible strains in plastic components should be taken as follows:

Material	*Maximum permissible strain* (per cent)
thermoplastics (except polystyrene)	1·0

polystyrene	0·5
thermosets (except phenolics)	10·3
phenolics	0·2

4. *Other factors.* The stiffness of a plastics material is also affected by other factors such as moulding and post-moulding storage conditions, and the presence of liquids (for example nylon 66 is appreciably softened by atmospheric moisture even at normal humidity). If a plastics component is likely to be operating at close to its limit of capability then these factors should be given careful consideration.

Fatigue properties

A plastics material that is subjected to oscillatory loading may fail by fatigue, in a similar way to that observed in metals. Fatigue data are available for a number of materials, but the values quoted are valid only in certain specific conditions and may therefore change if these conditions alter.

The fundamental conditions affecting fatigue are any change in (1) load, (2) temperature, (3) humidity, and (4) operating speed. These cause slightly different effects in each plastics material or specific grade of material, and proving tests should therefore be carried out.

Certain additional features should also be borne in mind. Humidity can have various effects on a particular material, depending on the nature of the environment, and may result in reduced fatigue-resistance. Thus corrosive environments may significantly detract from the material's capability. Variable performance may arise as a result of processing conditions; for example, tool temperature changes may result in a change in crystalline structure, lack of pressure or reduced cycle time may result in a lack of consolidation in the moulding, and stress may be moulded in. An indication of the importance of the process conditions is illustrated by the case of acetal: here it has been established that a moulding cycle that ensures that mouldings are produced to an approved minimum weight results in homogeneity and good performance in fatigue conditions.

Consistency of performance demands guidance from the designer in terms of product requirement and evaluation procedure. The designer should also provide feedback to the processor so that quality standards can be set and maintained throughout.

Frictional properties

While there are many occasions when lightly loaded or slow speed bearings will operate successfully, sometimes without external lubricant, caution should normally be exercised and proving tests should be carried out in any significant design application. As with fatigue properties a quoted performance value is valid only for certain specific conditions, and may change with any change in conditions.

Used as bearing surfaces, moulded thermosetting materials are only suitable for very light or intermittent duty since the inherent hardness of the resin binder and the relative difference in hardness of the filler systems appear to present an undesirable surface. However some phenolic and epoxy laminates are used as bearings on some large equipment.

Thermoplastics materials are more usually selected for bearing surfaces. They may be subject to great variations of load, temperature, operating speed, surface topography, and so on. Comparison of quoted properties of different materials is difficult, and any unproven design specification is therefore undesirable practice.

The following features of the frictional properties of plastics should be borne in mind.

1. Although properties of metals vary, values for fundamental properties of plastics are in general much lower than those of metals, and surface deformation characteristics also differ.
2. Materials having apparently similar functional properties may have quite different reactions to abrasion caused by the introduction of dust or other particles on to the significant surface. For example, it is claimed that where nylon is used as a bearing surface, particles that are introduced may be absorbed into the nylon so that the effect is minimal.
3. Since material performance may be affected by temperature it is important that the anticipated service temperature is known.
4. Since surface deformation, and therefore areas of surface contact, are time dependent, the coefficient of friction may increase at low speeds and decrease at higher speeds.
5. Materials may be affected by moulding conditions, for example, crystallinity is affected by temperature variations, and post-ageing operations may cause some surface oxidation.
6. The frictional properties of plastics products can be improved by addition of lubricants such as graphite. Similarly external lubricants such as water, oil, etc., may usually alter the frictional characteristics to advantage, with more success on plastics–metal interfaces than on plastics–plastics interfaces. However, a lubricant must be chosen which will not be absorbed by the plastics material and which will not attack the surface by initiating chemical bonding of the sliding faces.

For further information on friction and wear see Bowers and Zisman (1964).

Resistance to impact

Impact strength data are probably of greater importance in initial evaluation and quality control than they are to the designer. It is perhaps preferable to consider toughness as one of the important properties of plastics materials from a design point of view. A protective cover in pressed metal may be permanently distorted if dropped from a given height, but if the cover is made from an appropriate plastics material the energy of dropping will be partially absorbed, so that the consequent distortion will be less, and of a temporary nature only. The thickness of the test specimens, the velocity of the test, and the temperature all have considerable effect on the resistance to impact. The characteristics of each material are considerably influenced by the presence and shapes of notches; and processing and the state of dryness of the material have further effect.

In general, the impact resistance of more rigid materials is not good. It should be borne in mind that while the type of filler used in thermosetting materials influences impact resistance, long-fibre fillers increase the costs of finishing. Rubber and modified resins have been used successfully as fillers for thermosetting materials, improving impact resistance.

Where an impact load is applied some advantages can be gained from the use of thermoplastics materials, the selection of which should be based on service temperature requirements. Some materials which are acceptable in normal ambient conditions are liable to break at sub-zero temperature (for example, polypropylene homopolymer embrittles at 0°C), and requirements for service at low temperature necessitate the use of copolymers.

At sub-zero temperatures high-impact polystyrene shows no real advantage over ordinary polystyrene, whereas polycarbonate and polyphenylene oxide, both of which are tough materials, perform well. Those materials which have high moisture-absorption characteristics do not perform satisfactorily at sub-zero temperatures. The designer should also be aware that a material which performs well under isolated impact blows may not be as adequate as an alternative material when the impact blows are of lower force but greater frequency.

Solvent resistance

Any plastics component will need to have a particular set of qualities, depending on the function it is required to fulfil. Resistance to all or some of the following may be required: battery acid, lacquers, detergents, edible fats, oils and petrol, certain gases, and even water. No plastics material will perform successfully in all environments, and applied or moulded-in stress or increase of temperature will increase the possibility of attack by solvents.

It is necessary that the designer should have prior knowledge of the worst conditions and possible hazards likely to be encountered in the life of the product; he must also be aware that a fault may possibly be inherent in the design. Incorrectly assembled screws or rivets, or greases for lubrication of moving parts when taken on trust from an untried source of supply, may set conditions for future solvent cracking or crazing.

Solvents can affect plastics in the following ways:

1. The material may absorb the solvent, resulting in swelling (but no other visual changes) and a change in its properties. For example, absorption of water by nylon will increase impact strength but reduce tensile strength; absorption of oil by polypropylene may influence impact strength at low temperatures only; and absorption of either water or oil reduces impact strength of some phenolics.
2. True solvent attack results in surface degradation followed by complete dissolution of the material if the attack is maintained; this usually occurs with thermoplastics. This feature is utilized in the production of adhesives for thermoplastics—for example, acetone for cellulose acetate, toluene for polystyrene, and dichloroethylene for acrylics.
3. Certain solvent conditions may cause stress cracking in many thermoplastics. To the designer this is the most troublesome of solvent effects since it may be overlooked if, in proving, the components are produced and assembled with a low stress, but alterations to production techniques may later cause changes in the characteristics of the product. Where critical conditions apply, values for known torques, clearance holes for self-tapping screws, loading, etc., should be clearly stated.

A typical problem which could arise in service occurs where an unplasticized material, such as acrylic, is designed as part of an assembly containing a plasticized material, such as polyvinyl chloride. Initial proving may have given satisfactory results because the incorporated plasticizer was non-migratory. However most plasticizers are not completely retained in the polyvinyl chloride as it ages, and they tend to migrate so causing some attack to the acrylic, possibly resulting in surface attack or crazing. Unless the required type of plasticizer is specified (in this case, as non-migratory to acrylic) unsuitable plasticizers may be supplied, resulting in service failure of the acrylic and possibly of the whole assembly.

The effect of solvents used in lacquers, paints, or cleaning solutions that are applied to thermoplastics materials must always be considered. Their effects should, preferably, be prevented by reduction of moulded-in stress and by annealing of components prior to treatment; otherwise alternative treatments or methods of preventing faulty work must be considered.

Table 1 provides approximate values for the performance of various useful plastics in the presence of solvents used in the motor industry. This may be used as a guide to material selection, bearing in mind that other materials and conditions may also require to be considered, and confirmation of suitability of a specific material for a particular application should always be obtained. For further guidance on the effect of solvents literature available from the Rubber and Plastics Research Association of Great Britain should be consulted.

It should be noted that where plastics materials are

Table 1. Resistance of plastics to various fluids

	Water			*Petrol*			*Oils*			*Grease*			*Sulphuric acid* (s.g. 1·3)			*Detergent*			*Non-aqueous cleaners**		
(°C)	20	60	80	20	60	80	20	60	80	20	60	80	20	60	80	20	60	80	20	60	80
Phenolics (wood-filled)	5		8	3A		5A	2A		3A	2		5	5		9	5		9	2		4
Phenolics (mineral-filled)	1		3	3A		5A	2A		2A	1		2	4		8	2		4	1		2
Ureas	7		8	3A		5A	1A		2A	2		5	5		9	7		9	1		2
Polyesters	2		7	3A		5A	1A		2A	1		2	5		7	2		8	1		3
Nylon 66	8B		9B	2B		3B	2B		4B	1		1B	8		9	8B		9B	3B		5B
Nylon 11	4B		8B	2B		3B	2B		4B	1		1B	3		9	4B		8B	1		3B
Acetals	1		2	1		2A	1		2	1		3	8		10	1		3	1		3
Acrylics	1		2	2C		6C	1C		3C	1C		3C	2		4	1		2	10		10
ABS	1		2	3ABC		8ABC	3ABC		6ABC	2ABC		2ABC	2		5	2		3	10		10
Polypropylene	1		1	4B		6B	4B		7B	1B		4B	1		2	1		1	3B		7B
TPX (polyolefin)	1		1	5B		8B	4B		7B	1B		4B	1		2	1		1	10		10
Cellulose acetate	5B		7B	2AB		6AB	5AB		6AB	4AB		5AB	9		10	8B		9	10		10
Polystyrene	1		1	10AC		10AC	7AC		9AC	5AC		7AC	1		1	1		2C	10		10
Surlyn A (ionomer)	1		1	2		3	5		7	3		5	1		2	1		2	10		10
Polyphenylene oxide	1		1	10A		10A	4B		8B	2B		6B	3		5	1		1	10		10
Polyethylene	1	1		8B	10B		4B	8B		4B	6B		1	2		10C	10C		5BC	10BC	

*Non-aqueous cleaners include such compounds as trichloroethylene, carbon tetrachloride, and white spirit.

Note:
A solvent attack
B absorption and swelling
C crazing and stress cracking
0–10 is resistance rating ranging from 1 (good) to 10 (poor).

in contact with foods, not only is it necessary to ensure that the foods do not attack the plastics but also, of even greater importance, that the plastics do not contaminate the food.

Heat resistance

The designer must establish the degree of heat-resistance required in the product, basing his calculations on the anticipated ambient temperature and, in the case of some parts such as electric-motor components, the additional heat generated as a working unit. Where there is demand for service in warmer climates, the increased ambient temperature must be taken into consideration. It must also be borne in mind that, since plastics are extremely good thermal insulating materials, a part may function satisfactorily in a metal component but not in a plastics component.

In the case of plastics the effects of temperature cannot be considered alone since time, temperature, and load have combined effects that can influence reliability of a product. Many test results could be misleading if considered independently. The approach taken by the motor vehicle industry is first to make an assessment of requirements, after which suppliers can be consulted for more specific comparisons of materials. This can be supported by work to determine the effect of temperature in the particular area under investigation.

Thermosets. Those thermosetting materials that offer greater dimensional stability at room temperatures (for example, phenolics and alkyds) also offer the best performance at temperatures up to 230°C. Those filled with the more inert materials (such as glass, asbestos, and mica) offer greater resistance to creep under load at elevated temperatures, but the resin chosen must be such that decomposition does not occur at such temperatures.

Polyester dough-moulding compounds have been used with success at temperatures up to 160°C, and certain special grades can be used at even higher temperatures; but loss of volatiles and loss of weight generally occur and confirmation that the material performs satisfactorily in each particular application must be obtained. For temperatures up to 180°C and in cases where their properties and processing methods are advantageous, melamines and granular polyester compounds may also be considered. However features such as shrinkage of melamines or requirements such as resistance to electrical tracking must always be borne in mind.

Wood-filled phenolics withstand the normal assembly loadings in general automotive applications at temperatures up to 100°C. At temperatures greater than 100°C some of these materials will creep under prolonged stress and difficulties may arise, such as the failure, as a result of this tendency, of plastics components to maintain critical dimensions or the slackening of nuts assembled to a known torque. These difficulties may be avoided by selection of a grade of material in co-operation with the material supplier.

Thermoset mouldings shrink on temperature-ageing, by 0·2 per cent for wood-filled materials and by up to 0·1 per cent for those materials having more inert fillers. Where required, stabilization of thermosetting mouldings by heat treatment may be specified. For wood-filled phenolics this is effected by 12–16 h at 95–105°C, and for heat-resistant materials by 1–2 h at maximum service temperature. Where heat treatment is at temperatures in excess of 130°C the temperature should be raised from room temperature in programmed 30 minute, 50°C steps followed by slow cooling.

Thermoplastics. Thermoplastics materials are in general suitable for maximum working temperatures in the range 60–150°C, depending on the type of thermoplastics; and their performance can be improved by use of glass-fibre fillers. Characteristics showing the combined effects of time, temperature and load are however far more variable, and below the melting point the following two types of change must be considered.

1. Reversible changes occur when with increasing temperature the material becomes less rigid and therefore less resistant to an applied load. This change, which can occur at temperatures from 40–100°C, depending on the material, and which reverses on cooling, may be sufficient to have allowed creep in what was apparently a satisfactory product.
2. Irreversible changes occur when long-term application of temperatures is sufficient to initiate instability. They may result in loss of plasticizer from material such as PVC or cellulose acetate, or oxidation (which is probably most critical in materials such as nylon or polypropylene). Exposure to high temperatures for a long period may even cause chemical rearrangement in some materials.

Plasticizers, which are added to compounds in order to aid flow, flexibility, or ease of processing, do not usually form part of the chemical structure of the material and are retained in the moulded product until ageing or some external factor, such as heat, causes surface changes which allow their loss to the atmosphere or to an adjoining material. If the adjoining material is susceptible to attack from the migrating plasticizer it may crack or craze, or become bonded to the material initially incorporating plasticizer. The plasticizer may simply condense onto a nearby surface and in this context it is always necessary to monitor the condition of electrical contact metals in such an environment. Oxidation is a surface effect which develops progressively into the body of a moulding as heat ageing progresses and results in changes in properties. Difficulties arising by oxidation or from the use of plasticizers are usually negligible providing the service environment is first taken into consideration and the possible results are anticipated.

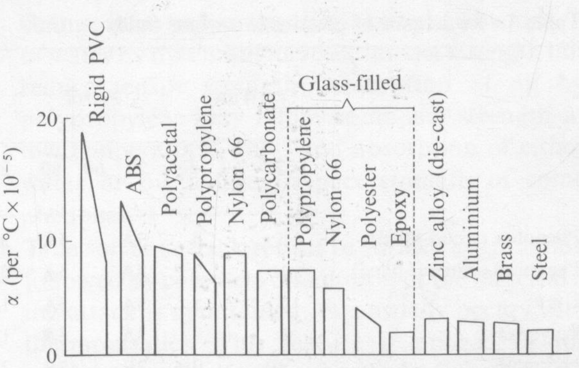

Fig. 1 Coefficients of linear thermal expansion (α) for various materials (Courtesy of Lucas Electrical Ltd.)

Increase in temperature may also cause varying expansion in different materials (see Fig. 1). This may result in differential movement, and its effects on a composite assembly should be allowed for (for example, by the use of slotted holes).

Thermoplastics mouldings shrink on temperature ageing as do thermosets. Shrinkage may be up to 0·5 per cent, and depends not only on the type of material but also on the amount of stress in the mouldings. For critical uses, annealing or stabilizing is recommended for each material, but since such treatment affects dimensions it must be specified in the first instance so that an allowance for the dimensional change can be made in tool design.

It is not easy to specify the safe use of thermoplastics materials for all applications at elevated temperatures. However Table A2.1, Appendix 2, provides a simple guide for selection of materials prior to carrying out proving tests.

Methods of moulding

This section outlines the various production processes and their effects on the material properties of the product.

Thermosets

Compression moulding. The material to be moulded is placed in a mould (*tool*) that is split to form punch and die, and which can be heated to the required temperature to initiate flow and complete cure. The required pressure is applied by means of a simple two-platen vertical press. The tool is charged with about 7–15 per cent excess material in order to allow for that escaping between the dies as flash during the moulding operation.

The best tooling will give flash thickness of up to 0·15–0·20 mm, but, owing to tool wear, variation of temperature, and inconsistency of flow in materials, it is not possible to establish close tolerance requirements over this limit. Unless reasonable tolerance can be allowed the designer must be prepared to machine the final product. Flash must usually be removed; its removal from fibre-filled materials is more difficult since it leaves a witness.

Compression-moulding of products containing delicate inserts may result in damage to the inserts by the increased pressures. Some inserts can be assembled in a secondary operation.

A homogeneous, fully cured moulding produced by compression moulding will in general give the best electrical insulating properties. Use of very high tool temperatures may, however, cause rapid surface curing of material and internal porosity ('cokiness') which can lead to distortion and lowered electrical performance.

Transfer moulding. In this method tools are first closed under pressure and the material is then loaded into a separate pot adjacent to the die cavity. The material is forced by a plunger from the pot through a runner and gate system into the cavity where curing then takes place. The significant advantages of this method are the ability to mould around delicate inserts or toolforms, and, in general, an improvement in the speed of cure. The location and size of the gate through which the material is forced into the cavity is significant.

Transfer moulding of long-fibre-filled materials generally results in some loss of mechanical strength because of breakdown of fibres. Depending upon the complexity of the flow path of the material, it may also result in some loss of electrical insulation properties.

Flow into the cavity may sometimes create a pattern of differential stress that will result in minor distortion or dimensional changes after moulding, or in a post-stoving operation, or both. If it is important that such changes do not occur then suitability of the process should be confirmed.

Injection moulding. In this process material is forced through a heated cylinder by a screw or plunger, and passes into a runner system from which it is fed through a gate into a closed and heated tool with a cavity (or cavities). Curing takes place in the cavity whilst the screw or plunger is retracted and the cylinder recharged with material. It is essential that the temperature reached in the cylinder does not cause too rapid a cure since this would reduce the free-flowing characteristics of the material.

Most of the effects of this process on the product can be allowed for by a careful consideration of a tool design before it is committed.

The dimensional stability, distortion and shrinkage, and electrical insulation properties of the product will be influenced by the location of the gate and the size of the runner system. The designer should therefore check that this process will allow the requirements of the product to be met. Material-flow parameters must also be set and maintained in order to avoid inconsistencies of product properties. This requires co-operation and liaison with material suppliers.

If multiple impressions are being considered, care must be taken to ensure that material losses in the runner will be at a minimum. Alternatively, 'cold' runner systems can be used, where the material in the runner is prevented from curing and can be progressively used in following mouldings.

Chrome-plated tools are usually considered a necessity for this process. The designer should bear in mind that the design should not be altered after plating has been carried out. In general injection moulding is not suitable for production of large, flat mouldings; these should preferably be produced by compression moulding.

Thermoplastics

Injection moulding. For the injection moulding of thermoplastics components the material passing through the cylinder must be maintained at a temperature which will ensure plasticity and flow, while the tools must be maintained at one which is sufficiently low for the material to cool below its softening point so that the moulding can be extracted.

The thickness/flow strength ratio must allow adequate filling of the mould cavity without the formation of unnecessary moulded-in stressed areas. If, for example, a material under correct conditions will flow from a point of entry in the cavity for a distance of 150 mm in a moulding which is 2 mm in thickness, the only feature which will improve the ratio is (1) the positioning of the gate so that flow takes place in more than one direction and total flow is added, or (2) increasing the thickness of moulding. The increased thickening may be local, using ribs, providing note is taken of the importance of the rib sections (see p. 11) and the change in flow pattern that these may cause. The use of warm rather than cold tools may assist in avoiding stressed areas. It should be borne in mind that the moulding company to be employed will possess considerable technical expertise on these points, and should always be consulted.

The design requirements for dimensional change or distortion must be realistic with regard to the material to be used. There may be difficulties in the production of close-tolerance parts from high-shrinkage materials.

Processing costs will depend on (1) the difficulties inherent in injection moulding of a particular material, and (2) any features in the design which interrupt the regularity of production. For example, lack of draft on side walls may result in difficulty in ejecting the part from the mould, complicated cores in tools may lead to tool wear and flash, and the moulding-in of inserts may require an irregular stoppage of the moulding cycle for insert loading.

It must be ensured that the manufacturer selected to carry out the moulding has machines of the correct capacity for the product. In general the material plasticising-capacity of the machine must be greater than the weight of the product by a factor of 1·5–2. Using a machine with a capacity that is either too large or too small may result in an inconsistent product.

Extrusion. In the simplest form of extrusion, material is conveyed through a heated cylinder by means of a screw. A die which provides the required cross-sectional shape of the continuous extrusion is assembled on the nose of the cylinder. The extrusion is cooled (usually by passing through a water bath) as it leaves the die, thus ensuring that the shape is maintained.

The process is used for a variety of applications such as the production of rod, bar, tube, sheet, and film, and also for the covering of wire, and for the production of tubular *parisons* for blow moulding. Since each application presents its own difficulties, a specialist in each particular process should always be consulted.

The material used for extrusion often differs in molecular weight or melt viscosity from that used for other methods of moulding, with the result that similar products manufactured by different processes will have different properties, even though the same basic polymer is used. Orientation in an extruded product may lead to substantially different properties in and across the line of flow.

Care should be exercised in confirming prototype product performance if parts machined from extruded bar are used when this will not be the ultimate method of production.

Vacuum forming. Vacuum forming of plastics material is carried out by sealing sheet plastics over a chamber containing a die form; the sheet is heated to a temperature at which it can be deformed by atmospheric pressure, and a vacuum is applied to the cavity. There are many variations of this basic process, which result in a product with improved form, stability, and consistent sheet thickness.

Most materials have a *plastic memory*, that is they tend to revert to their original shape as soon as conditions allow; thus at higher temperatures thermoplastics vacuum formings will revert to sheet. The most stable vacuum-formed thermoplastics products are those produced from sheet heated throughout its mass, which is then cooled in the manner least likely to produce forming stresses prior to removal from the mould. If one of the requirements of the product is that it should remain stable at some specific temperatures during its life it is essential that these conditions are specified.

Sheet material is much more expensive than material in granular form and, as in sheet-metal work, the cost of offcuts can be a significant part of the product cost. The process will usually be more economically viable for thin components than for thick ones which are often more easily produced by other means. However, if quantities are small, tool costs are low.

Rotational moulding. Here a measured amount of material is placed into a moulding tool which is in the form of a hollow chamber. While the chamber is heated the tool is rotated in a controlled manner in different planes; the material melts and adheres to the walls where it flows to form a continuous skin. The tools are then cooled and the moulding is extracted.

This process is successfully used for production of very large containers and for smaller hollow articles. It may also be used for production of containers, such as American petrol tanks, having an outer layer of one material (for example, polyethylene), and an inner lining of another (for example, nylon).

The allowable limits of permeability must always be specified when containers are to be used for liquids or gases. The designer must also specify the acceptable variations in wall thickness of the moulding. Mould costs of rotationally moulded products are relatively low. For further information on rotational moulding see British Plastics Federation (1972).

Blow moulding. In this process extruded tubular parisons are used to produce both hollow articles and continuous tube. For production of blow-moulded containers the extruded tube is fed into split dies of the determined final shape. The dies are then closed and air is introduced, inflating the tube, which then takes the shape of the die cavity. For production of continuous tube (thin 'layflat' polyethylene tube for manufacture of plastic bags) the extruded tube is closed as it begins to leave the extruder head, and the tube which follows is inflated by air which is introduced through a device located in the extruder head.

This process is competitive with rotational moulding for production of containers up to the size of the conventional domestic dustbin; containers larger than this are usually produced by rotational moulding. Both processes however are limited in the range of materials that can be used and each has its own particular advantages.

It should be borne in mind that only certain materials, principally polyolefins and PVC, are readily suitable for processing by this method. Many materials are unsuitable and others can be processed only with difficulty. Irregular shapes can be produced; but production of irregular sections is difficult and often impossible. It is essential that the service requirements that might cause stress cracking are determined, and that material choice and design are such that these difficulties are avoided.

For high-speed production of hollow articles or continuous tube the product requirements should be determined by the designer in collaboration with the manufacturer.

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Design considerations

This section describes (1) the general factors necessary to achieve an effective design using plastics materials, and (2) the more important detailed aspects of such designs.

Selection of materials

Many data on plastics materials, based on laboratory testing, can be obtained from suppliers and research organizations; and this allows comparison with other materials tested under the same controlled conditions. To be effectively used this information must be examined in conjunction with many other data derived from consideration of the finished product or component.

Plastics materials are of interest to the designer because they have the following properties:

(1) they can be readily formed into complex shapes (a single plastics moulding can often replace an assembly of metal parts);
(2) they are light-weight and of low density;
(3) they do not corrode;
(4) finishing processes, for decorative or protective purposes, are not necessary;
(5) many machining operations can be eliminated;
(6) they are self-coloured;
(7) costs are relatively low;
(8) they have self-lubricating properties;
(9) they are transparent or translucent;
(10) in certain applications they are capable of absorbing sound and vibration;
(11) they have good electrical-insulation properties; and
(12) they have good thermal-insulation properties.

The low modulus of elasticity of plastics materials tends to confuse the inexperienced designer since the metals to which he is accustomed are at least one order of magnitude stiffer.

Compared with metals, plastics have the following general disadvantages:

(1) they have lower strength;
(2) they are less hard and less elastically ductile;
(3) they have higher thermal expansion;
(4) they are more susceptible to creep, cold flow, and deformation under load;
(5) they are flammable;
(6) they are subject to low-temperature embrittlement;
(7) they are subject to degradation by heat, light, and chemicals etc.; and
(8) they are less resistant to abrasion.

No one plastics material has features which are wholly desirable or wholly undesirable; good design will optimize the use of the best properties whilst minimizing the possible disadvantages.

Some general rules

Although plastics are important in modern technology, the good designer will also consider the use of metal casting, pressing, auto-machining, etc., before coming to a decision.

The use of plastics materials should be approached in a manner similar to that of traditional metals. Plastics are suitable for many engineering applications and the usual design and development principles can be applied from project stage to engineering production. Their use must first be defined; this includes specification of load, environment, service life, colour, quantity requirements, etc. Modern engineering design practice attaches great significance to the product specification, and physical conditions which the product may have to undergo must be clearly defined (for example, immersion in water).

The designer should first determine the use and general requirements from a check list (see Appendix 3) before selecting the material and determining the process. The preliminary design scheme can now indicate whether a component produced from a particular plastics material is likely to function satisfactorily and reliably, whether it will be economically viable and whether it will be of good appearance. It will be more likely to fulfil these requirements if in the design the following basic rules, many of which are illustrated in Appendix 4, are followed:

(1) aim for simple mouldings;
(2) keep moulded sections as uniform as possible;
(3) design radii as large as possible in order to avoid sharp inside corners;
(4) avoid side holes and oblique holes, since these require complicated moulding tools, and are difficult to maintain and easily broken;
(5) design generous *draw* (internal cavity);
(6) use beading to disguise flash witness and mismatching of two separate mouldings, or mould split lines;
(7) avoid depressed lettering and any lettering on curved surfaces since this increases the cost of moulds;
(8) avoid threads ending on the face of the moulded piece since these are formed by a tool with a knife edge of steel, which may break off;
(9) avoid countersunk-headed screws, since, on tightening, these may exert a pressure which breaks the moulding;
(10) avoid holes or inserts near the edge or face of the moulding, since adjacent thin sections may crack;
(11) avoid long side-holes with no provision for support of the steel pins used to form them, since these may bend or break in the moulding process;
(12) avoid irregular-shaped inserts projecting from the surface of a moulding, since the mould

must be cut to receive them and accuracy may be difficult to maintain;

(13) avoid large metal inserts, since differences in thermal expansion create stresses (small metal inserts are preferable);

(14) remember that a steel mould is a receiver gauge for metal inserts—they must be accurate;

(15) tolerance must be as wide as possible; close tolerance mouldings can be produced but they are expensive; and

(16) remember that moulded screw threads shrink in pitch as well as in diameter.

After these rules have been taken into consideration the designer should consult the following check-list.

1. Are the requirements of the moulding realistic, and are they precisely stated?
2. Will the moulding provide adequate performance, or are the properties higher than will be required?
3. Is the design of the moulding suitable for production in plastics or is it too closely based on or a copy of that of a metal component?
4. Have the possibilities and cost of *over-design* or conversely, the even greater cost of *under-design* been considered?
5. Does the design have appropriate built-in reliability?
6. If the design was based on a previous one (perhaps because of service exigencies), have circumstances or materials changed so that the design now includes superfluous or unnecessarily expensive parts or processes?
7. Can any standard moulding be used instead?
8. Does the design permit subsequent operations, such as automatic assembly?
9. Are material requirements correctly known (for example fatigue stresses, 'hot spots', harsh environments, etc.)?
10. Can expensive materials (restricted to strategic places, such as on surfaces) be used in conjunction with ones of lower cost?
11. Has the materials specialist been consulted in order to ensure that use is being made of up-to-date materials available from mass production or batch products?
12. Is the form of the moulding as simple as possible?
13. Are sections as uniform as possible?
14. Have all 'corners' the maximum radii permissible?
15. Have adequate tapers been used to aid extraction of the moulded parts?
16. Are tolerances the maximum allowable?
17. Have automatic moulding techniques been taken into account?
18. Does the design cater for easy finishing (such as flash removal by tumbling), and are secondary operations reduced to a minimum?
19. Have those responsible for the toolmaking and moulding processes been consulted?
20. Can the moulding be sprung to clip on to assembly parts if necessary?
21. Can the moulding be welded (by solvent, heat, radio-frequency, ultrasonic, etc.)?
22. Can single- or two-component adhesives be used (single-component ones are always preferable in production)?

Component thickness

A plastics part should be designed with the minimum thickness necessary to provide the required properties, but not so thin that moulding becomes difficult and creates unforseen problems resulting from moulded-in stresses. Thickness must be as uniform as possible in order to eliminate distortion, internal stresses, and cracking, and any change of section must be gradual. Where there is a change in thickness (for example at a boss) provision of fillets of generous radii will reduce any stress concentration introduced by sharp corners.

Thermosets. The acceptable minimum thickness for unstressed thermosetting mouldings is generally considered to be 2·2–3·0 mm. Variation in thickness can most readily be tolerated in thermosetting materials. However, in order to achieve a constant density and hence greater dimensional stability, such variations are best catered for in the moulding process by careful placing of the material in compression moulding, and by location of the feed in transfer or injection moulding. When practicable, high-frequency preheating of material prior to moulding will result in maintenance of homogeneity of mouldings with dissimilar sections.

In order to obtain increased strength without increased moulding thickness, changes are sometimes made in the type of filler incorporated in the material, for example, a fibre filling may be preferable to a wood filling. The disadvantages of such a change should be borne in mind, as should the fact that a specific impact load that breaks a wood-filled moulding may also cause a crack to appear in a material which is reputed to have increased strength. If such a crack results in service failure no advantage is gained.

Thermoplastics. The determination of a satisfactory minimum wall thickness is more difficult in the case of thermoplastics materials, but for medium-sized mouldings (0·1–0·5 kg) a thickness of 1·8–2·0 mm will usually ensure that mouldings have generally good properties at an economical price. At this thickness, particularly with the more complex mouldings, it is important that (1) good toolmaking ensures constant thickness to avoid influencing the pattern of material flow, and (2) the tool designer takes into account the flow pattern and the distortion effect before determining the shape and position of the gate.

When components are stressed in processing or assembly it may be necessary to increase the thickness (for example to 2·5 mm), but any such increases must be accompanied by other modifications, namely increased radii in corners, correct moulding conditions, and adequacy of material feed.

It should be borne in mind that correct placing of suitable ribbing on thin sections will increase rigidity and strength where required, without necessarily increasing process time, and with only nominal increase in material cost. It is important, however, to keep the thickness of such ribbing to less than 60 per cent of the nominal thickness of moulding if sink marks (depressions in the moulding caused by material shrinking into the ribs) are to be avoided on the surface.

Small mouldings in nylon, polyacetal, polycarbonate, and polythene have been produced satisfactorily with thicknesses of 0·5 mm, but at these values the designer must confirm that temperature resistance and rigidity are satisfactory. Attempts to mould polypropylene, ABS, and some rigid thermoplastics at this thickness may well produce components with a poor resistance to shock loadings, particularly at sub-zero temperatures. The parameters governing flow and viscosity should be set to close limits, and maintained within them.

Where metal inserts are to be incorporated in a moulding it is necessary that the thickness should not only allow consolidation of material around the insert, but that it should be sufficient to withstand any applied loading (that may be either tensile or torsional) that may occur in service at a particular temperature.

Use of inserts

An insert is an integral part of a plastics moulding and consists of metal or other material that may be moulded into position. Inserts usually provide load-bearing supports for parts subsequently attached to the moulding; their design and positioning must be such that the mechanical strength of the plastics–insert combination is adequate.

Good mechanical anchorage of the insert in the moulding is of prime importance because there is rarely any natural adhesion between plastics materials and the metals used for inserts. This anchorage must therefore be arranged to prevent movement under load.

When considering the use of inserts the designer must bear in mind that they are employed to overcome a failing in a local area of the plastics material, and it is therefore necessary to ensure that stress is not transferred to a weaker part of the moulding.

Diamond-knurled round stock is commonly used for smaller inserts. Where this type of design is satisfactory it is preferable to hexagonal-section bar since here the corners tend to set up local stresses in the surrounding moulding. Ideally inserts should be manufactured from materials having the same coefficient of linear expansion as the moulding, but in practice this is difficult.

The use of inserts always introduces difficulties into the moulding process. Accurate placing of the insert in the mould is time-consuming and increases costs. Where tools are made to receive inserts, the tool acts as a gauge in which an oversize insert will not fit, and an undersize insert will probably allow material (flash) to flow over the working face of the insert, thus causing scrap and possibly resulting in the need for a secondary operation to remove it. Where possible it is best to avoid inserts, for example by the use of self-tapping screws or moulded slots and standard nuts.

Finishing and decoration

Most plastics materials can be dyed or pigmented to attractive shades, and the surface finish, being a replica of the mould surface, can be of high gloss. Finishing as such can therefore be limited to removal of flash, drilling of holes, or similar operations, and finishing processes such as painting and plating are generally not necessary.

The following points should be borne in mind by the designer, who is required to determine the finishing treatments where necessary.

1. Parting lines in tools always leave visible marks on mouldings; suitable detail design can ensure that these do not detract from the finished appearance.
2. Where witness results from removal of flash after moulding (this is more usual with thermosetting mouldings) not only is it more likely to detract from the appearance, but, in the case of filled materials, it exposes the filler to the environment and thus may create a different surface condition.
3. Minor surface discrepancies can result in the need for polishing, which when carried out on thermoplastics materials may introduce surface stresses causing some surface disintegration in service. This can be avoided by suitable design of surface contours.
4. Machined parts may be so stressed that they require annealing after machining. The designer should check whether, by using the known properties of the material, the design could be improved to remove the need for machining.
5. Where electroplating or vacuum-deposited coatings are required the designer must bear in mind that the basic principles of these processes still apply, for example recesses must be adequate to receive the coating, and sharp corners should be avoided.
6. When parts are to be painted, solvent systems or temperature of cure of the appropriate paint system may dictate the material to be used.
7. Annealed parts may change in dimensions; if selective decoration requires the use of masks, it

must be ensured that matching tolerances are adequate.

Economics of plastics moulding

When considering the least expensive approach to the correct use of plastics materials it is necessary to examine all the factors that might influence final cost—that is material costs, processing costs for moulding, forming and finishing, production tooling, and moulding-machine factors.

Material costs

Historically, while the cost of metallic materials has been continually rising the comparative cost of plastics materials has in general been steady or decreasing, notwithstanding the situation recently brought about by the world energy crisis and increased oil prices. However, in the long-term this crisis will alter the cost relationship both between the various plastics materials and between plastics and metals; but there is no doubt that the continuing growth in the use of plastics will be sustained.

The moulding materials available may be divided into (1) those which are used in large-scale manufacturing and which are usually of lowest volume cost (for example polyolefins, polyvinyl chloride, polyamides, phenolics, and styrenes) and (2) those which are used in relatively small-volume manufacture and which are of high cost (for example polyphenylene sulfide, silicones, and fluorines). The latter materials usually have some particular high-performance property that justifies their application.

In general the lowest material cost for a product is achieved by the use of those materials that are employed in larger volumes, particularly when these are standardized so that they can be purchased in bulk quantities, which provides further price advantages.

The designer should not ignore new materials which are expensive when newly introduced. Large-volume production of a new material usually takes from two to eight years to get under way after the market possibilities have been examined by small quantity application. During this trial period it is advisable to consider the material's potential for design in the future.

Processing costs

After purchase at the best possible price, perhaps the most important factor in maintaining low cost is the effective utilization of the material purchased. This is largely determined by the nature of the process itself and by the processability of the material.

The moulding of thermosetting materials usually involves overloading of the tool, resulting in a material loss of 7–20 per cent of the weight of the component. Scrap mouldings, furthermore, are not usually recycled and are therefore of no value. Effective utilization of these materials would be expected to be from 75–92 per cent, with a reasonable average of about 85 per cent. This is also true of injection moulding where sprue and runner systems are lost.

By comparison, the efficient use and proportionate re-use of thermoplastics materials should yield a material utilization of about 90 per cent. This however can be affected by many factors, one of the commonest of which is changeover of material on a machine, which accounts for a major part of the losses. There are 'best' material sequences in a moulding machine, and recommendations for individual materials that should be followed to obtain the maximum yield. Similarly, on start-up or close-down of a moulding-machine sequence, obeying a correct procedure (which does not include indiscriminate purging) will reduce losses during breaks. Changeover difficulties which unavoidably result in a high material loss occur with some materials, for example, polycarbonate. Losses during the moulding of polycarbonate can be reduced if an economic batch size is established and orders for mouldings are placed such that the machine is used for production in this material for as long as possible before changing to some other material. This may result in an accumulation of as much as three months' stock of moulded parts, but these will not deteriorate. Efficient utilization of material is usually assisted by automatic moulding, but this may not be economical for short runs of complicated components.

Consideration of the amount of material necessary for vacuum forming or similar methods of production from sheet must take into account the losses from offcuts which may amount to 25–50 per cent of the total material used. Material utilization in rotational casting or blow-moulding processes approaches 100 per cent. It is thus essential for the designer concerned with cost savings to consult with colleagues and, where appropriate, outside suppliers in order to establish a balance between raw material costs, wastage, and batch size and its resulting stock and financial consequences in order to achieve a compromise which optimizes all factors.

The removal of flash from a thermosetting moulding can be expensive, and the use of long-fibre-filled materials for shapes with awkward recesses can involve hand trimming at a cost that is out of all proportion to that of the moulding. The designer should consider the cost of finishing and whether it is excessive; it should be borne in mind that (1) use of an alternative material may reduce the cost of finishing, (2) it may not in fact be necessary to remove flash completely, and (3) the significance of flash might be reduced by alteration of the detail design.

Production tooling. The following features should be taken into account in the manufacture of a moulding tool: (1) adequate hardness and finish, (2) facility of extraction, (3) temperature control, and (4) production of a specific number of products (impressions) during each cycle. Each of these features will affect the cost of both the moulding tool and the product. It should also be borne in mind that an adequate and repeatable standard of quality can only be achieved using the correct tool.

The following are the factors affecting the initial decision on moulding-tool manufacture:

(1) quantity requirements and product life, which will affect the decision in relation to machine size and hence the number of components to be produced or the number of tools; and
(2) rate of production and material characteristics, which will alter heating or cooling requirements.

There will also be many supplementary considerations depending upon the particular product required and the time factors involved.

Where tools are purchased from an outside source it is necessary that requirements be clearly defined, and that it is clearly understood what is covered by the toolmaker's quotation. This will avoid any confusion that might arise from widely differing estimates. In Britain some advice may be sought from the Gauge and Toolmakers Association.

Moulding-machine factors. The capital outlay for the purchase of a moulding machine, and its running costs, must be recovered over a specific time, as must the service charges which include consumables, energy, maintenance, and operating costs. These costs are normally relative to the size or capacity of a machine. Mouldings produced within a specific period will carry an appropriate proportion of this machine cost, and it follows that increased output within the given time will reduce specific cost. Maximum output is therefore of prime importance. Output is reduced where thickness of moulding or difficulty of ejection (because of lack of taper, etc.) are governing factors in the machine closing or opening time.

Unless much more expensive moulding tools are used the loading of inserts can normally only be carried out while a press is open, so that for this period of time the machine is not working. It may therefore be advisable to assemble inserts by means of a secondary operation, depending upon material. This may be accomplished mechanically by riveting or other alternative fixing arrangements, such as ultrasonics or by the use of adhesives. The use of adhesives is expensive, however, and is not generally recommended.

Since no single plastics moulding company has the best facilities for producing all types of mouldings it is important that the designer should know which suppliers are best suited to supply particular mouldings.

General considerations

It is not practicable to compare production costs of a moulding over a range of materials and processes. However, since most requirements can usually be met by more than one plastics material or method of processing, the following list of criteria may be used as an aid to selection. The least expensive material is that which:

(1) meets the full technical requirements of the product;
(2) is of the lowest cost, having taken into account anticipated efficiency (such as process losses);
(3) will process in a consistent manner with the minimum of reject products; and
(4) involves the minimum of expenditure in secondary operations.

The least expensive moulding tool is that which:

(1) is designed to allow for the material characteristics;
(2) is sufficiently robust to minimize the effects of damage or wear; and
(3) will produce the required quantity of mouldings in a regular manner.

The least expensive machine is that which:

(1) adequately processes the material concerned without degradation or difficulty;
(2) matches in capacity the volume requirements of the product; and
(3) can cycle repetitively at the desired speed without damage or wear.

Dimensional control

The successful use of plastics mouldings requires a proper understanding of the dimensional accuracy that can be achieved at reasonable cost. A conventional approach by a designer with experience in setting limits on machined parts will, however, certainly cause difficulties: metal parts rarely distort or change dimensionally after machining and even after heat treatments physical change is small, whereas plastics parts are subject to relatively large dimensional changes occurring after moulding and before final use. It is rarely necessary to use the conventional approach adopted for metals since, in practice, the inherent flexibility of plastics materials can be adapted by such design features as force or clip fits.

Shrinkage

The shrinkage of plastics materials that occurs on cooling after moulding may be increased by conditions during moulding or by an unsuitable environment, and may result in distortion of the product. Data on shrinkage, usually referring to the difference in dimensions between the moulded product after cooling and the cold-moulding dieform, is provided by material suppliers. This shrinkage is brought about by the combined action of thermal contraction (plastics have relatively large coefficients of linear expansion), and moulded-in stress which is caused in part by molecular re-orientation. These factors generally become less significant if fillers are incorporated in the material, the different types and quantities of which are particularly significant in thermosetting materials.

High-shrink thermoplastics materials are subject to significant variation in shrinkage, which is dependent on moulding thickness, tool temperature, and moulding pressure.

Thermosets. Shrinkage among thermosetting materials ranges from zero for a low profile polyester dough-moulding compound where a shrinkage control additive is incorporated, to 1·3 per cent for a nylon-filled phenolic. It is therefore important that a correct choice of material is made before tooling is designed.

A manufacturing tolerance for a material and a variation in product type that affects the quoted shrinkage may demonstrate that even an ideally stored material may still give a final shrinkage of the product that differs by as much as 15 per cent from that noted in suppliers' literature. Because of the hygroscopic nature of the unmoulded materials poor storage conditions will result in even higher shrinkage. It should be borne in mind that variation is more significant if the material is of high shrinkage: for example, if shrinkage is as high as, say, 1·0 per cent variation may be 0·2 per cent, whereas with low shrinkage, say, 0·2 per cent, the variation may be only 0·04 per cent.

This variation is generally not excessive when measured samples are produced from controlled moulding cycles at controlled temperatures. The variation brought about by the component shape can be corrected if conditions of moulding are established and maintained, and important dimensions in the tool are not finally cut until mouldings have been made in the unfinished tool so that actual shrinkage is confirmed. Shrinkage variations arising from poor conditions of storage or from processing variations (such as variable weight of charge) or from preheating are not under the control of the designer, but none the less should be borne in mind. The design of thermosetting plastics components that are reasonably constant in dimensions is generally ensured by attention to reported shrinkage and by control of process and storage.

Compromises may have to be made as regards material properties. For example, a heavily mica-filled phenolic may be selected to meet close-tolerance requirements, but other less desirable properties such as brittleness may then cause difficulties. Thus a compromise choice may have to be made as regards these properties.

Thermoplastics. These exist as crystalline materials, such as nylons, acetals, and polypropylene, and as amorphous materials, such as acrylics and polystyrenes. Shrinkage from the molten state is generally greater for crystalline materials (1·5–2·5 per cent) than for amorphous materials (0·5–0·8 per cent). As with thermosetting materials, the greater the shrinkage the more variation in shrinkage can be expected.

The most significant characteristic of thermoplastics materials is their reaction to the deformation process in moulding. This reaction results from the re-orientation of the molecular structure, and can be likened to stretching a coil of wire. Whilst the material is plastic, and flowing into the mould, these helical molecules tend to be stretched by the applied forces. On cooling, the stretched helices set in position but, under the influence of intermolecular forces, they tend to revert to their original orientation. Thus shrinkage in the line of flow can be as much as 15 per cent greater than shrinkage across the line of flow. Shrinkage can also be influenced by rate of cooling, pressure, product shape, and production speed. In order to lessen these effects it is important that the moulding-tool designer should take these parameters, and also the position of material entry (gating) of the die, into consideration.

For important dimensions, final correction of the tool is necessary after moulding conditions have been established. It is significant that, with correct design and moulding, production of gears in higher shrinkage materials (such as nylons and acetals) has proved satisfactory all over the world; full-width fascia units produced from crystalline and amorphous materials have been fitted to metal structures in automobile production, with minimal discrepancy; and engineering applications in general continue to increase.

Other aspects of shrinkage. Ageing, a process which may be speeded up by any increase in temperature, brings about further post-moulding shrinkage. This shrinkage arises partly from the release of moulded-in stress, and is therefore influenced by the quality of the moulded product. In some materials, for example nylon, this shrinkage may be partly counteracted by absorption of ambient moisture.

Whilst ageing generally has less effect on thermosetting materials than on thermoplastic materials, it should be noted that the post-moulding shrinkage, after heat ageing, of urea or melamine formaldehyde materials may be very close or equal to the shrinkage from the mould: that is 0·5–0·7 per cent. Dimensional changes occurring in thermoplastics components with ageing are dependent upon component shape and material. If the effects of ageing are of importance they should be established by testing.

At some stage in their service life most products are subjected to high humidity, the effects of which must be determined. Although other properties may vary, most materials do not undergo significant dimensional changes under these conditions, but some materials are affected, for instance, various types of nylon, cellulose acetate, and some urea formaldehyde or long-fibre-filled phenolic materials.

Moulds must be manufactured to a specified tolerance and their component parts must fit or slide together. The more complex moulds may be difficult to produce to exact dimensions, and special considerations may therefore have to be given to dimensional tolerances, for which it is unfortunately not possible to provide any general rules.

Ejection from the tool, depending on the component shape, is effected by shrinkage of material in the mould. High-shrinkage materials will shrink onto punch form and tool projections, and low shrinkage materials may not readily leave the die cavity. A desirable draft allowance is 2° per side for internal forms and 1° per side for external forms.

Tolerances

Guidance on achievable tolerances for plastics mouldings are provided by BS 2026: 1953; BS 4042: 1966, and by material suppliers.

Dimensional tolerances of mouldings produced entirely within one mould part can be smaller than those for mouldings formed across the parting line of moulds (that is, those that are affected by thickness of flash). Mould-part positioning, for example by dowels, can affect concentricity and alignment, and 'splits' on moulds introduce difficulties.

Finer tolerances than those recommended by British Standards can be achieved at a cost. For example, a single cavity may be used for the entire production; material may require special control in storage and accurate metering to the machine; it may be necessary to protect the moulding machine from draughts from doors or windows which can temporarily chill the moulds; improved control of temperatures, pressures, and times during the moulding process may be necessary; and some post-moulding stabilization treatment of the mouldings may be required. Having produced mouldings to an exact size, controlled conditions of storage and service life are necessary if the sizes are to be maintained, but in practice it is best to avoid such strict tolerances by means of suitable design.

Tolerances for mouldings in thermosetting materials, excluding those made by cold-moulding, post-forming, or fabricating processes, are specified in BS 2026 which recognizes four normal classes as follows:

a *Class I tolerance*. The narrowest possible limits on selected dimensions commensurate with closely controlled and supervized processing at all stages in production.

b *Class 2 tolerance*. The tolerance obtainable on selected dimensions by extra care in processing.

c *Class 3 tolerance*. The tolerance representing normal process variations and reasonable economy.

d *Class 4 tolerance*. Wide variation where dimensions are not important, e.g. the dimensions of handles, knobs, etc.

The relationship of classes of tolerances, taking Class 3 as unity is as follows:

Class 1. 0·4 times Class 3 tolerances
Class 2. 0·6 times Class 3 tolerances
Class 3. 1·0 times Class 3 tolerances
Class 4. 1·6 times Class 3 tolerances.

Requirements for screw threads, which shrink in pitch as well as in diameter, are a special case and are not included.

Tolerances for mouldings in thermoplastics materials depend significantly on type of material, shape and size of component, and degree of control in moulding. BS 4042: 1966 presents a system of dimensional tolerances for small injection mouldings. This and manufacturer's literature should be read in full since isolated extracts taken from these documents may be misleading.

Closer tolerances than those specified in BS 2026 and BS 4042 are generally only achieved in production by taking special care with those materials which have a shrinkage from the mould cavity of less than 0·7 per cent. A material with low mould shrinkage, high temperature resistance, low moisture absorption, and preferably containing a filler will be the most stable in dimension, and, providing its other properties are acceptable, should be selected when close tolerance is required.

Process standards and quality control

Once the production process has been selected the designer must balance the potential of that process against the requirements of the product. The necessary criteria to be maintained, which in their simplest form will be the accepted tolerances of various dimensions and the material specification, must then be noted on the component drawing. Instructions may include specific items such as, for phenolics for example, a specified maximum acetone extract which denotes a degree of cure. In the case of thermoplastics the drawing may denote an area within which a feed or gate may not be placed because of the effect of localized stress in the component, or it may show that the material must be tested before use to determine those parameters which affect the moulding process.

These instructions, which are the basis on which quality standards are determined, should be sufficiently complete to ensure that the product gives a good service performance. They will usually refer only to the moulding, without consideration of environmental factors or secondary operations that may cause some change to occur. Changes will often depend on the conditions of the process selected and the following factors should be borne in mind.

1. Changes may occur in parts after moulding as a result of the relief of stress as the parts leave the pressurized condition, or by continued shrinkage particularly with high-shrinkage materials, or, with certain types of nylon, by absorption of moisture. Except in critical applications where pre-conditioning or annealing prior to dimensional checks are stipulated, quality control checks

should be carried out not less than 24 hours after moulding.

2. Where post-stoving or annealing operations are carried out, including (or equating to) secondary operations applied to the assembly containing the product, further shrinkage will occur, and the specification requirement after this treatment should be verified.
3. If a moulding is stressed in a solvent (such as grease or a liquid) during service, this should be simulated in the quality-control procedure. Testing of representative samples of a batch of mouldings may be adequate, but, where lubricants are an essential part of an assembly, standards must be exacting.
4. The designer should bear in mind that, although the quality engineer will check that the mouldings conform to the given specification, it is his responsibility to ensure that any variables which affect the end result are given in the specification.

Moulding for electrical uses

Plastics have long been established as materials for use as insulation in electrical applications. These applications, which cover a wide range of voltage and frequencies, vary from miniature electronic devices, cables, and miscellaneous switchgear to structural uses in antennae. In general, modern plastics materials compare favourably with the long-established insulating materials such as slate, marble, hard rubber, and glass, and they may on occasion approach the excellence of quartz without having its fabrication disadvantages.

In the hands of the experienced designer plastics are extremely effective as electrical insulators, but the selection of a material for a particular application must take into account not only its electrical characteristics but also its mechanical, thermal, and chemical properties, and the environment to which the part is subjected. Since these considerations will often dictate the materials to be used, they must be the first to be established.

The following are examples illustrative of requirements that must be considered when selecting a material.

1. The amount and type of plasticizer in the PVC covering for a cable may be dictated by the degree of flexibility required over a particular temperature range.
2. A laminate produced to meet the mechanical requirements of panels and switchboards may have a base fibre arrangement that will lead to irregularities in electrical insulation (undirectional effects).
3. Switch-boxes or switch bases may be mounted in acidic, oxidizing, or other unsatisfactory environments, and in domestic applications they may be splashed with animal fats and subjected to the effects of condensation.
4. Oils, petrol, steam, and salt water are a few of the hazards encountered by the electrical insulation of motor vehicles, and ultraviolet radiation can have variable and significant effects on external switchgear.
5. Ageing of plastics may lead to surface deterioration in which contamination from external sources may lodge, and this in turn may result in failure.

Most of the basic factors that require consideration in electrical design are common to all insulating materials and are well known to electrical engineers; those especially applicable to moulded plastics components are noted in the following paragraphs.

Dielectric strength

Dielectric strength may be defined as the electric stress (V/m) which an insulating material can successfully withstand. This is an important property of moulding materials used for electrical insulation; values of 5–50 kV for 3 mm thickness are usual, the structurally simpler polymers generally giving the higher values.

Dielectric strength is recorded under standard conditions in most published data. These conditions usually refer to temperature and time, for example 1 min value at 90°C, and because of the differing potential applications, such as in film for coils or capacitors, or in mouldings in bulk, reference is also made to the thickness of material tested.

Since time, temperature, and thickness each have an effect on dielectric strength, and since this is also affected by the reaction of the material to the rate at which voltage is applied, no single value will generally determine the design parameters. Typical curves, illustrated in Fig. 2, show the effect of these variables on a phenolic material.

Features regarding dielectric strength that are important to designers are as follows.

1. Breakdown of a product can be effected by, for example, contamination, porosity, and voids. The application of this test parameter can therefore be useful, whether or not the product is required to have a high electrical performance, because discrepancies in mouldings affect other performance parameters, such as tensile, impact, creep, and fatigue properties.
2. On heat-ageing, most thermosetting materials show an increase of dielectric strength which is dependent upon the type of resin and filler involved. This increase, which is probably due to some further cross-linking and the elimination of trapped gases or moisture, may be maintained in dry conditions providing the heat ageing has not been such that decomposition of the material has occurred. Thus greater electrical stability may be introduced by a heat-treatment operation between moulding and use.