Design with Plastics*

THE KEY to any successful part development is the proper choice of material, process, and design matched to the part performance requirements. The ability to design plastic parts requires knowledge of material properties—performance indicators that are not design or geometry dependent—rather than material comparators that apply only to a specific geometry and loading. Understanding the true effects of time, temperature, and rate of loading on material performance can make the difference between a successful application and catastrophic failure. Examples of reliable material performance indicators and common practices to avoid are presented in this article. Simple tools and techniques for predicting part performance (stiffness, strength/impact, creep/stress relaxation, and fatigue) integrated with manufacturing concerns (flow length and cycle time) are demonstrated for design and material selection.

Engineering plastics are now used in applications where their mechanical performance must meet increasingly demanding requirements. Because the marketplace is more competitive, companies cannot afford overdesigned parts or lengthy, iterative product-development cycles. Therefore, engineers must have design technologies that allow them to create productively the most cost-effective design with the optimal material and process selection.

The design-engineering process involves meeting end-use requirements with the lowest cost, design, material, and process combination (Fig. 1). Design activities include creating geometries and performing engineering analysis to predict part performance. Material characterization provides engineering design data, and process selection includes process/design interaction knowledge. In general, the challenge in designing with structural plastics is to develop an understanding not only of design techniques, but also of manufacturing and material behavior.

Engineering thermoplastics exhibit complex behavior when subjected to mechanical loads. Standard data sheets provide overly simplified, single-point data that are either ignored or, if used, are probably misleading. Some databases provide engineering data (Ref 1) over a range of application conditions, and knowledge-based material-selection programs have been written (Ref 2). A methodology for optimal selection of materials and manufacturing conditions to meet part performance needs is described in this article. Simple tools and techniques for the initial prediction of part performance, leading to the optimal selection of materials and process conditions, are discussed. Related coverage is provided in the articles “Effects of Composition, Processing, and Structure on Properties of Engineering Plastics” and “Design and Selection of Plastics Processing Methods” in this book.

Mechanical Part Performance

There are a wide variety of part performance requirements. Some, such as flammability, transparency, ultraviolet stability, electrical, moisture, and chemical compatibility, as well as agency approvals, are specified as absolute values or simplified choices. However, mechanical requirements such as stiffness, strength, impact, and temperature resistance cannot be specified as absolute values. For example, a part may be required to have a certain stiffness—maximum deflection for a given loading condition. The part geometry (design) and the material stiffness combine to produce the part stiffness. Thus, it is impossible to select a material without some knowledge of the part design. Similarly, the part may be required to survive a certain drop test and/or a certain temperature/time/loading condition. Again, it is impossible to select a material or design a part by using traditional, inadequate, single-point data such as notched Izod or heat distortion temperature (HDT). In addition, it is important to consider the effects of the design and material selection of a part on its fabrication. Considerations such as flow and cycle time should be quantitatively included in the design and material-selection process. Simple yet extremely useful tools and techniques for the initial prediction of part performance are presented in this article.

The design process for thermoplastic part performance can be divided into two categories based on time-independent and time-dependent material behavior (Fig. 2). For time-independent material behavior, elastic material response is used to predict the displacement of a part under load. The maximum load occurs when the strength of the material is reached as fully plastic yielding for ductile materials or brittle failure for glass-filled materials. Time-dependent material behavior becomes important for three types of loading: monotonic loading at a given strain rate until failure occurs, constant load for a period of time, or cyclic load. In the first case, strain-rate-dependent material behavior becomes important; for constant load or displacement, time-dependent deformation or stress relaxation becomes an important design consideration; for cyclic loading, fatigue failure is an important consideration. In the next five sections, stiffness, strength, impact, creep/stress relaxation, and fatigue behavior are related to part performance. More details of these important design issues can be found in Ref 3.

Part Stiffness. Many thermoplastic parts are plate-like structures that can be treated as a simply supported plate, possibly reinforced with ribs. A procedure intended to provide quick, approximate solutions for the stiffness of laterally loaded rib-stiffened plates has been developed (Ref 4). The computer program employs the Rayleigh-Ritz energy method and is capable of including the geometric nonlinearities associated with the large displacement response typical of low-modulus materials such as thermoplastics. The program allows the user to input the important parameters of specific plate structures (length, width, thickness, number of ribs, rib geometry), the boundary conditions (simply supported, clamped, point supported), and the loading (central point, uniform pressure, torsion loading). With the capability of multiple rib pattern definitions, the user can quickly determine the load-deflection response for different designs to select the one that is most effective for the specific application. This tool has been validated with finite-element results. An example demonstrating the prediction of the nonlinear load-displacement response is shown in Fig. 3.

Strength and Stiffness of Glass-Filled Plastic Parts. An accurate characterization of the strength and stiffness of glass-filled thermoplastics is necessary to predict the strength and stiffness of components that are injection molded with these materials. The mechanical properties of glass-reinforced thermoplastics are generally measured in tension using end-gated, injection-molded ASTM type I (dog-bone) specimens (Ref 3). However, the gating and the

direction of loading of these molded specimens yields nonconservative stiffness and strength results caused by the highly axial orientation of glass that occurs in the direction of flow (and loading) during molding.

Previous studies (Ref 5) have shown that injection-molded, glass-reinforced thermoplastics are anisotropic; that is, stiffness and strength values in the cross-flow direction are substantially lower than in the flow direction. The tensile stiffness and strength were measured by using dog-bone specimens that were cut in both the flow and cross-flow directions from edge-gated plaques of various thicknesses. The ratio of the cross-flow/flow tensile modulus and strength of 30% glass-filled polybutylene terephthalate (PBT), 30% glass-filled modified polyphenylene oxide (M-PPO), and 50% glass-filled (long glass fibers) nylon are plotted versus specimen thickness in Fig. 4 and 5. It is important to note the strong dependence of the cross-flow/flow ratio on specimen thickness and the small values of this ratio for small specimen thicknesses. These data clearly indicate that material selection and design for glass-filled materials that are based on injection-molded bars of a given thickness could be totally misleading—cross-flow properties could be only 50% of flow properties (small specimen thicknesses), and unless the thickness of the specimen is the same as the thickness of the part, the data could not be used for predicting part performance. However, for most parts (thickness less than 4 mm, or 0.16 in.) with glass loadings of 30% or greater, a simple mold-filling analysis coupled with an anisotropic stress analysis with the cross-flow stiffness of 60% of the flow stiff-

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**Fig. 1** Design-engineering process. The goal is to meet the end-use requirements the first time with low cost.

**Fig. 2** Design for thermoplastic part performance. (a) Time-independent. (b) Time-dependent

**Fig. 3** Nonlinear pressure-deflection response for a 254 by 254 mm (10 by 10 in.) plate with a thickness of 2.5 mm (0.1 in.) and a material with a modulus of 2350 MPa (340 ksi)

**Fig. 4** Ratio of cross-flow/flow tensile modulus as a function of specimen thickness. PBT, polybutylene terephthalate; M-PPO, modified polyphenylene oxide

**Fig. 5** Ratio of cross-flow/flow ultimate stress as a function of specimen thickness. PBT, polybutylene terephthalate; M-PPO, modified polyphenylene oxide
Part Strength and Impact Resistance. A number of test methods such as Izod (notched beam) and Gardner/Dynatup (disk) are available for measuring impact resistance (Ref 3). Such tests should not only measure the amount of energy absorbed, but also determine the effects of temperature on energy absorption. Additionally, they should be able to identify strain-rate-dependent transitions from ductile to brittle behavior. They should be applicable to a wide variety of geometric configurations. Unfortunately, these techniques provide only geometry-specific, single-point data for a specific temperature and strain rate. Also, each test provides a different ductile/brittle transition. Energy absorption, however measured, is made up of many complex processes involving elastic and plastic deformation, notch sensitivity, and fracture processes of crack initiation and propagation.

The prediction of strength and impact resistance of plastic parts is probably the most difficult challenge for the design engineer. Tensile stress-strain measurements as a function of temperature and strain rate provide one piece of useful information. Most unfilled engineering thermoplastics exhibit ductile behavior in these tensile tests, with increasing strength (maximum stress) as displacement rate increases and/or temperature decreases. However, stress-state effects must be added to the tensile behavior because the three-dimensional stress state created by notches, radii, holes, thick sections, and so forth increase the potential of brittle failure.

Ductile-to-brittle transitions in the fracture behavior of unfilled thermoplastics occur with increasing strain rates, decreasing temperatures, and increasingly constrained stress states. Figure 6 shows three common mechanical test techniques: uniaxial tension, biaxially stressed disks (usually clamped on the perimeter and loaded perpendicular with a hemispherical tup), and notched beams loaded in bending. These three tests provide uniaxial, biaxial, and triaxial states of stress. Typical part geometries and loadings exhibit combinations of these states of stress. Thus, no one test is sufficient for part design and material selection. Furthermore, there are two competing failure modes: ductile and brittle (Fig. 6). With increasingly constrained stress states (uniaxial \(\rightarrow\) biaxial \(\rightarrow\) triaxial), the tendency for brittle failure tends to increase. Brittle failure occurs when the brittle failure mechanism occurs prior to ductile deformation (Fig. 6).

The calculation and measurement of the ductility ratio (Ref 6) is a method to characterize the ductility of a material for a relatively severe state of stress, for example, a beam with a notch radius of 0.25 mm (0.010 in.). The ductility ratio is defined as the ratio of the failure load in the notched-beam geometry \(P_{\text{failure}}\) to the maximum ductile load-carrying capability in an unnotched-beam geometry where the height of the unnotched beam is equal to the net section height of the notched-beam geometry:

\[
\text{Ductility ratio} = \frac{P_{\text{failure}}}{P_{\text{ductile}}} \quad \text{(Eq 1)}
\]

where:

\[
P_{\text{ductile}} = \frac{\sigma f bh^2}{l} \quad \text{(Eq 2)}
\]

and \(\sigma f\) is the strength at appropriate rate and temperature, \(b\) is the beam thickness, \(h\) is the beam height, and \(l\) is the beam span.

This ductile load limit can be determined experimentally or with this plastic-hinge calculation assuming fully developed plasticity over the entire cross section and perfectly plastic material behavior. A ductility ratio of 1.0 corresponds to a ductile failure, while ductility numbers less than 1.0 correspond to varying levels of brittle behavior. Ductility ratios can be plotted as a function of strain rate at different temperatures to create fracture maps such as the one shown for polycarbonate (PC) in Fig. 7. This information is useful for material-selection and initial part design considerations.

**Creep/Stress Relaxation—Time/Temperature Part Performance.** Polymers exhibit time-dependent deformation (creep and stress relaxation) when subjected to loads. This deformation is significant in many polymers, even at room temperature, and is rapidly accelerated by small increases in temperature. Hence, the phenomenon is the source of many design problems. Development and application of methods are needed for predicting whether a component will sustain the required service life when subjected to loading, as the useful life of the part could be terminated by excessive deformation or even rupture. For most practical applications of polymers, predictive methods must account for part geometry, loading, and material behavior.

A common measure of heat resistance is the heat-distortion temperature (HDT). For this test, bending specimen 127 by 12.7 mm (5 by 0.5 in.) with a thickness ranging from 3.2 to 12.7 mm (0.125 to 0.5 in.) is placed on supports 102 mm (4 in.) apart, and a load producing an outer fiber stress of 0.46 or 1.82 MPa (66 or 264 psi) is applied. The temperature in the chamber is increased at a rate of 2 °C/min (3.6 °F/min). The temperature at which the bar deflects an additional 0.25 mm (0.010 in.) is called the HDT or sometimes the deflection temperature under load (DTUL). Such a test, which involves vari-

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**Fig. 6** Impact test methods exhibiting various states of stress (\(\sigma\)). (a) Tensile test—uniaxial stress state. (b) Dynatup test—biaxial stress state. (c) Notch Izod test—triaxial stress state. (d) Competing failure modes

**Fig. 7** Fracture map for polycarbonate
In order to use the deformation maps for design purposes, the stresses, strains, and environmental factors must be accounted for. The deformation maps are generated from the experimental data obtained under various conditions, and they provide a means to estimate the behavior of the material under similar conditions. The deformation maps are typically used in conjunction with finite element analysis (FEA) to predict the behavior of plastic parts under service conditions.

The deformation maps are generated by measuring the deformation of a test specimen under various loads and temperatures. The deformation is then plotted against the load and temperature, and the resulting deformation map is used to predict the behavior of the material under similar service conditions. The deformation maps are typically used to predict the behavior of plastic parts under service conditions, such as load-bearing, thermal, and environmental stresses.

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urement of the amount of crack growth per cycle \((\frac{da}{dN})\) as a function of the cyclic range of stress-intensity factors \((\Delta K)\). Despite the fact that plastics are time-dependent materials, and that linear fracture mechanics only apply strictly to elastic materials, it appears that crack-propagation rates in many polymers can be correlated with \(\Delta K\).

During the fatigue process, the stress amplitude \((\Delta \sigma)\) usually remains constant and failure occurs as the result of crack growth from an initial, subcritical size to a critical size related to the fracture toughness \((K_c)\) of the material. The lifetime of a component is thus dependent on the initial crack size, the rate of crack growth, and the critical crack size. The relation takes the power-law form:

\[
\frac{da}{dN} = A \Delta K^n \quad \text{(Eq 7)}
\]

where \(A\) and \(n\) are material constants and \(a\) is crack length. Typical crack-propagation curves for a number of plastics (Ref 9) are shown in Fig. 9.

Fatigue lifetime of plastic parts can be calculated for design purposes by integrating the crack-growth rate expression (Eq 7) after substitution of Eq 8:

\[
\frac{da}{dN} = A Y^n \Delta \sigma^n a^{n/2} \quad \text{(Eq 9)}
\]

Assuming that the geometry factor \(Y\) does not change as the crack grows, this equation can be integrated to give the number of cycles to failure \((N_f)\) that is necessary for the crack to grow from its initial size \(a_i\) to the critical size \(a_f\). For \(n \neq 2\):

\[
N_f = \frac{2}{(n-2)A Y^n \Delta \sigma^n} \left( \frac{1}{a_f^{n-2}} - \frac{1}{a_i^{n-2}} \right) \quad \text{(Eq 10)}
\]

This expression can be used to predict the fatigue lifetime of a component with an initial defect of known size.

The fatigue lifetime (number of cycles to failure) of a part is strongly dependent on the applied load. \(S-N\) curves have been generated for a number of thermoplastics (Ref 10) at room temperature with a standard tensile specimen with a net cross section of 12.7 by 3.2 mm (0.5 by 0.125 in.). The tensile load was varied from a very small load (nearly zero) to various maximum loads (stresses). A sinusoidal waveform with a frequency of 5 Hz was used. Very little or no specimen heating occurred. By choosing \(S-N\) curves for the same materials—polycarbonate (PC), modified polyphenylene ether (M-PPE), and acrylonitrile-butadiene-styrene (ABS)—whose fatigue-crack-propagation behavior is displayed in Fig. 9, the \(S-N\) data can be combined with the crack-propagation data to compute the initial crack lengths (Eq 10). The final crack length \(a_f\) is computed from the fracture toughness of these materials. Thus, over the range of stresses for the \(S-N\) curves, the initial crack lengths can be computed. Ideally, these crack lengths would be independent of applied stress level. However, while there is some variation, the average crack length was computed and used in Eq 10 to “predict” the measured \(S-N\) data from the crack-growth-rate data. These results are shown in Fig. 10 for PC, M-PPE, and ABS. These data and this approach indicate the similarity of the \(S-N\) and crack-growth-rate methods of predicting part lifetime and suggest a method of utilizing both types of data.

Manufacturing Considerations

Flow Length Estimation. The ability to manufacture plastic parts using the injection-molding process is governed by the material behavior, part geometry, and processing conditions. Estimating the flow length of the resin into a mold of a given thickness is an important manufacturing consideration for the design engineer. One example of a generic tool (Disk-flow) is capable of analyzing radial flow and quantifying effects of material, geometry, or process changes (Ref 11). This tool is composed of a numerical flow analysis, automatic mesh generator, and menu-driven pre- and post-processors. No knowledge of simulation techniques is required, though a knowledge of injec-

![Fig. 9 Fatigue-crack-propagation behavior. ABS, acrylonitrile-butadiene-styrene; PC, polycarbonate; M-PPE, modified polyphenylene ether](image)

![Fig. 10 S-N data compared to crack-growth prediction. (a) Polycarbonate (PC); \(a_i = 0.013\) mm (0.5 mil). (b) Modified polyphenylene ether (M-PPE); \(a_i = 0.32\) mm (12.5 mil). (c) Acrylonitrile-butadiene-styrene (ABS); \(a_i = 0.23\) mm (9 mil)](image)
Design-based material selection (Ref 12, 13) involves meeting the part performance requirements with a minimum system cost while considering preliminary part design, material performance, and manufacturing constraints (Fig. 13). Some performance requirements such as transparency, Food and Drug Administration (FDA) approval, or flammability rating are either met by the resin or not. Mechanical performance such as a deflection limit for a given load are more complicated requirements. Time-

![Fig. 11](image1) **Flow length versus wall thickness predicted by Diskflow mold-filling analysis. Material, unfilled PC; mold temperature, 82 °C (180 °F); melt temperature, 335 °C (635 °F); maximum injection pressure, 103.4 MPa (15 ksi)**

![Fig. 12](image2) **In-mold cooling time versus wall thickness predicted from one-dimensional, transient mold cooling analysis**

![Fig. 13](image3) **Design-based material-selection process**
and temperature-reduced stiffness of the material is determined from the deformation map. Part design for stiffness involves meeting the deflection limit with optimal rib geometry and part thickness combined with the material stiffness. This part geometry can be used to compute the part volume that when multiplied by the material cost provides the material as compared to the plate with no ribs. The resin must be unfilled to maintain acceptable aesthetics. It is unribbed to minimize sink marks on the exposed surfaces. Finally, it must support a uniform load across its surface without deflecting more than 2.5 mm (0.10 in.). The enclosure is a 300 mm wide by 450 mm long by 100 mm high (12 by 18 by 4 in.) box (Fig. 14).

A series of analyses is performed using three resins to see how they perform under different conditions. These resins are representative of what is currently used in electrical enclosures (computer housings, office equipment, etc.). They are an unfilled M-PPO resin, an unfilled ABS resin, and an unfilled PC-ABS resin blend.

To examine the relative performance of each resin, the application requirements are varied in loading, environment, and manufacturing. First, the uniform load is varied from 150 to 1200 Pa (0.02 to 0.17 psi). Next, the ambient temperature the enclosure must withstand for 1000 h under load is varied from 20 to 80 °C (68 to 175 °F). Finally, the gating scenario is changed from edge gated to center gated to multiple gates.

Using a center-gated box at 40 °C (105 °F) for 1000 h, the uniform load is varied from 150 to 1200 Pa (0.02 to 0.17 psi). For each resin the optimal wall thickness is determined to support the load at the lowest variable system cost for each loading case. Figure 15(a) compares the normalized cost of the enclosure for each resin (Fig. 8). Simply increasing the thickness of the plate with no ribs to 3.5 mm (0.136 in.) would provide a design that would meet the deflection requirements. The penalty would be a 40% increase in material usage and an additional 8 s added to the cycle time. Choosing a material with more temperature resistance or initial stiffness is an option.

Example 2: Materials Selection for an Electrical Enclosure. The usefulness of this process can be demonstrated through another design example. In this case, a very simple five-sided box is chosen. The box is used as an electrical enclosure and must meet flammability requirements. This limits the number of candidate materials to examine more closely. Also, this enclosure is not painted, and therefore the resin must be unfilled to maintain acceptable aesthetics. It is unribbed to minimize sink marks on the exposed surfaces. Finally, it must support a uniform load across its surface without deflecting more than 2.5 mm (0.10 in.). The enclosure is a 300 mm wide by 450 mm long by 100 mm high (12 by 18 by 4 in.) box (Fig. 14).

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as the load is increased. As can be seen from this graph, the PC-ABS and M-PPO are virtually equivalent in cost, while the ABS is about 30% more expensive. While this may seem counterintuitive (ABS is less expensive per pound than PC-ABS or M-PPO), it is easily explained by examining Fig. 15(b), wall thickness versus loading. At this elevated temperature and long time (40 °C, or 105 °F, 1000 h), the ABS requires significantly more material to support the required load within the specified 2.5 mm deflection than either the PC-ABS or the M-PPO. This added material far outweighs the price advantage of ABS.

The cooling time is another factor that will increase the variable system cost of the ABS resin enclosure. As the wall thickness increases, the time to cool the part to ejection temperature will increase. The cooling time is also influenced by the thermal properties of each resin. Figure 16 contains a graph of the cooling time versus wall thickness for the three example materials based on one-dimensional transient heat-transfer analyses. The wall thickness for each resin to support 600 Pa (0.09 psi) at a deflection of no more than 2.5 mm (0.10 in.) is indicated on the graph. From this graph, it can easily be seen that, in this case, the cooling time for each resin will be very different.

Using a center-gated box that must support a 300 Pa (0.04 psi) load within a 2.5 mm (0.10 in.) deflection of 1000 h, the temperature was varied from 20 to 80 °C (68 to 175 °F). Figure 17(a) compares the normalized cost of these three resins as the temperature is increased. Initially, at 20 °C (68 °F) these resins have very similar variable system costs. As the temperature increases, the creep performance of each resin decreases. Figure 17(b) shows the creep modulus for each resin as the temperature changes. The creep modulus of the ABS resin decreases rapidly as temperature increases. The M-PPO maintains its stiffness longer, but eventually decreases rapidly while the PC-ABS performs better, because of the high creep resistance of the PC component of the blend.

The wall thickness to support the load must increase as temperature increases because the creep modulus decreases. This, in turn, increases the part volume and the cooling time, affecting the variable system cost. As the temperature increases, the cost rises to high levels (ABS at 80 °C, or 175 °F, 1000 h). If the application must withstand these temperature extremes, a higher-performance thermoplastic may be a better choice.

The process to manufacture this enclosure can influence how the enclosure will be designed and what material will be used. Using a box that must support a 150 Pa (0.02 psi) load within a 2.5 mm (0.10 in.) deflection in a 40 °C (105 °F) environment for 1000 h, the gating scenario is varied choosing three common configurations (Fig. 18): edge gate, center gate, and four gates. The minimum flow length necessary to fill the part is determined for each case based on the geometry of the enclosure and the gate position. The minimum wall thickness to allow each material to achieve this flow length, determined using the radial flow injection-molding simulation, is then used as a lower bound on the thickness optimization and is shown in Fig. 19(b). Figure 19(a) details the normalized cost versus minimum flow length (i.e., gating scenario). Initially, as the flow length increases (from four gates to center gate) the normalized cost does not change. The wall thickness necessary to support the load within the specified deflection is greater than the minimum wall thickness dictated by the flow-length constraint. As the flow length increases from the center-gated to the edge-gated case, the normalized cost increases because the wall thickness is now dictated by the manufacturing constraint rather than the loading condition. The gate placement now dictates the wall thickness that is necessary to fill the part.

There are other considerations that a design engineer can use to help determine the best material for an application. The strength of a resin over a range of temperatures may aid the engineer in determining if the part will fail under load. The impact performance of the resin, as indicated by the ductility ratio, can also be quite important. While it only indicates the impact performance for one specific geometry, and cannot be used in design, it does provide useful comparative information.

**Conclusions**

Material selection and engineering design of plastic parts can be a difficult task when there is a lack of effective and efficient design methods and the associated material data. However, methods are available to improve the design process by providing more accurate and effective predictive techniques. Fracture maps indicate the relative ductility of a material as a function of temperature and strain rate for a relatively severe stress state. A range of test data for different stress states from tensile tests, disk tests, and notched beams is used to predict part deformation and potential ductile-to-brittle behavior. For time-dependent deformation, such as creep or stress relaxation, deformation maps
can be combined with linear elastic calculations of part deformation to predict the time- and temperature-dependent deformation of the part. The cross-flow stiffness and strength of injection-molded glass-filled materials is sometimes only 50% of the stiffness and strength in the flow direction, especially for thin-walled parts. This must be accounted for in predicting part stiffness and strength. For predicting lifetime of parts subjected to cyclic loading, the combination of S-N data and crack-growth-rate data is useful because it provides two options: to use the S-N data directly or to use the initial defect size with the crack-growth-rate data. In either case, with the vast number of parameters that affect fatigue behavior, having more information is useful. The design methods and material data summarized here describe some effective and efficient techniques to select materials and design plastic parts.

REFERENCES