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Plastic Part Design for Injection Molding

An Introduction

ISBN: 978-3-446-40468-7

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If, for example, the ruler was produced in a balanced two-cavity mold, the volume flow rate through the sprue would be the total molding volume divided by the fill time, while the volume flow rate for each runner, gate, and cavity would be one-half that of the sprue because there are two flow branches.

Determine apparent shear rate: The shear viscosity of a polymer is a function of both temperature and shear rate (Fig. 2.26). The temperature of the HIPS melt has been specified earlier as 200 °C; however, the apparent shear rate in each flow section must be determined before the shear viscosity in each section can be determined from the set of apparent viscosity curves given in Fig. 2.25.

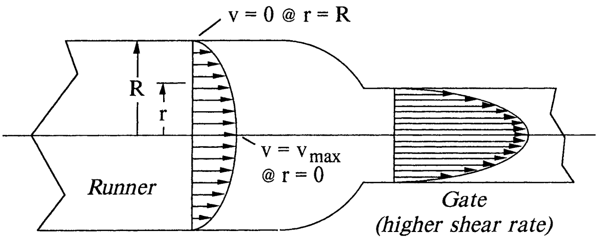

Figure 2.26 Apparent shear rate values vary with both flow rate and flow section geometry. The figure shows that the apparent wall shear rate in the gate is significantly higher than the one in the runner system due to the change in the velocity profile caused by the reduced cross sectional area

Laminar flow can be represented as layer-like flow with a velocity of zero at the wall and a maximum velocity at the center of the flow stream. The relative velocity of these adjacent layers results in a shear stress and molecular orientation or deformation. This velocity gradient (or shear rate) is greaterst near the wall, and at a minimum at the center of the flow stream. The apparent shear rate at the wall can be determined using:

Cylindrical flow channel $$\dot{\gamma}_a = \frac{4 \cdot Q}{\pi \cdot R^3} \tag{2.8}$$

Rectangular flow channel $$\dot{\gamma}_a = \frac{6 \cdot Q}{W \cdot H^2} \tag{2.9}$$

The shear rate also varies with volume flow rate and the flow channel geometry. For example, shear rates in the gate feeding the part tend to be higher than those in the runner due to geometry differences, as indicated in Fig. 2.26. Melt viscosities for most polymers tend to decrease with increasing shear rate due to its effect on molecular alignment (i. e., most plastic melts exhibit pseudoplastic flow behavior). Equations 2.8 and 2.9 have been derived assuming a Newtonian (parabolic) velocity profile. In reality, pseudoplastic polymers tend to have "blunt" velocity profiles, resulting in higher shear rates near the wall and lower shear rates towards the core in comparison with Newtonian fluids.

Table 2.3 Summary of isothermal mold filling analysis

Molding section	Section volume (in^3)	Volume flow rate (in^3/s)	Apparent shear rate (l/s)	Apparent viscosity		Pressure drop estimate	
				(Pa·s)	(lb·s/in^2)	(MPa)	(lb·s/in^2)
Sprue	0.154	0.782	259	320	0.046	2.1	306
Runner	0.110	0.782	510	270	0.039	4.9	716
Gate	0.004	0.782	1830	180	0.026	1.0	149
Cavity	0.905	0.782	312	305	0.044	11.4	1650
Total	1.173	—	—	—	—	**19.4**	**2820**

Determine apparent viscosity: The apparent shear viscosity of the polymer melt can be determined once the melt temperature and apparent shear rate values are known. In this case, the apparent shear viscosity values can be taken directly from the set of high impact polystyrene viscosity curves shown in Figure 2.25. Even though we are assuming a constant melt temperature (i.e., 200 °C), the viscosity in each section of the mold will be different, because the apparent wall shear rate in each section of the mold is different.

Determine the pressure drop: The total pressure drop, ΔP_{T}, associated with molding filling will be the sum of the individual pressure drops along the branch.

$$\Delta P_{\mathrm{T}} = \sum \Delta P_i = \Delta P_{\mathrm{sprue}} + \Delta P_{\mathrm{runner}} + \Delta P_{\mathrm{gate}} + \Delta P_{\mathrm{cavity}} \tag{2.10}$$

The individual pressure drops can now be calculated because the geometries, volume flow rates, and viscosity values are now known.

Cylindrical flow channel
$$\Delta P = \frac{8 \cdot Q \cdot \eta \cdot L}{\pi \cdot R^4} \tag{2.11}$$

Rectangular flow channel
$$\Delta P = \frac{12 \cdot Q \cdot \eta \cdot L}{W \cdot H^3} \tag{2.12}$$

The results of the isothermal analysis are summarized in Table 2.3. The mold filling pressure determined using Eq. 2.10 is an indication of the pressure at the instant of fill, as indicated in Fig. 2.16. While the absolute value determined here will clearly be in error (due to the large number of assumptions), this procedure assists the designer with flow balancing and other trending-type design decisions. A computer aided mold filling analysis is recommended whenever the option is available.

2.2.4 Flow Leaders, Flow Restrictors and Flow Hesitation

Flow Leaders and Flow Restrictions It is generally good practice to gate apart in such away that the melt flows as uniformly as possible through the cavity. Ideally, melt should flow from the gate region, reaching the extremities of the cavity all at the same instant in time. Consider the sprue-gated molding shown in Fig. 2.27. The part has a uniform wall thickness, and as a result, a disc or radial flow pattern is observed at the early stages of the mold filling process.

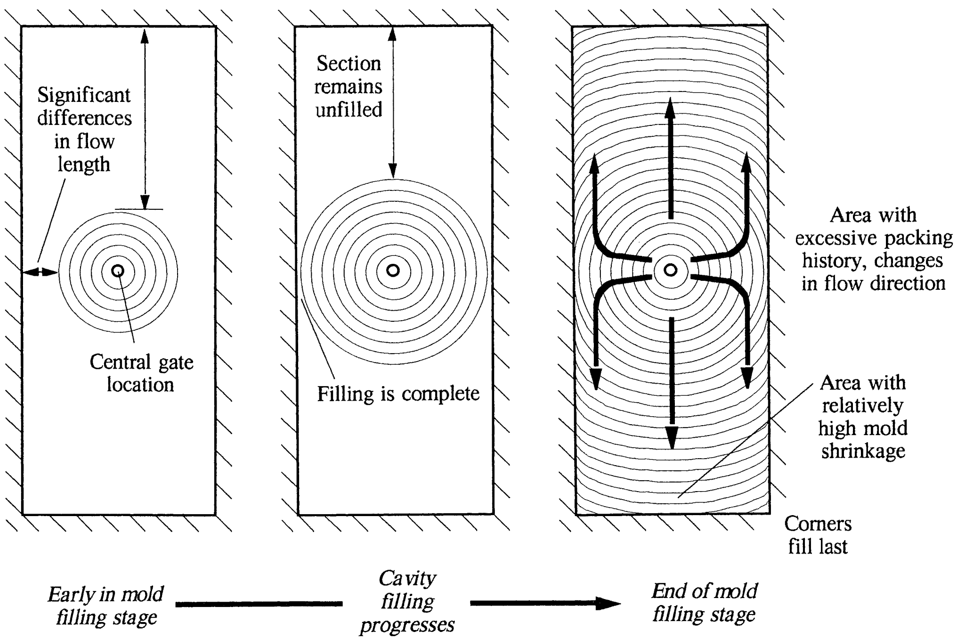

Figure 2.27 Central sprue gating of the rectangular part can result in overpacking in the gate region of the part as well as in changes in flow direction as the melt tunnels under the solid layer

The melt flow front reaches the left and right sides of the molding long before the upper and lower portion of the molding are filled out. This leads to an overpack/underpack situation and a problem with changes in flow direction as the melt tunnels under the solid layer. The net result is a part with variable shrinkage, residual stress, and a tendency to warp. Alternative gate locations for the rectangular molding are shown in Fig. 2.28. These gating schemes could be accomplished using a three-plate or hot runner tool configuration.

Like the single sprue-gated part, the part molded with two gates leads to an overpack situation and flow direction changes; however, to a lesser degree than the part molded with a single sprue gate. Note that when two gates are used, a single weld line is formed when the two flow fronts merge. Figure 2.28 shows that when three gates are used, the filling pattern is more uniform; however, the corner sections of the molding and weld extremities are the last places to fill. Of these three different gating schemes, the three-gate option appears to be the best in terms of flow path and packing uniformity, and would be suitable if the welds and the gate vestiges were functionally and esthetically acceptable.

While the three-gate option in Fig. 2.28 is an improvement, the corner sections of the part are still the last sections to fill. This is inevitable when you try to fill a constant thickness rectangular or square shape with a radial flow pattern. However, the filling pattern can be modified so that the melt flow front does reach the extremities of the cavity at the same time. In order to achieve a balanced fill, the filling pressure drop associated with each and

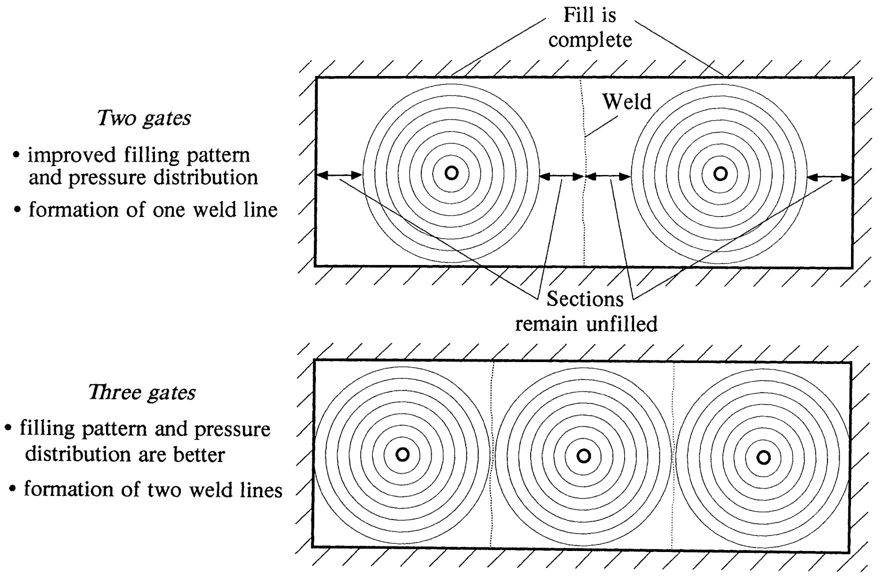

Figure 2.28 Increasing the number of gates improves the flow pattern and pressure distribution; however, this creates weld lines

every flow path from the gate must be equal (e.g., the pressure drop from the gate to a comer must be equal to that from the gate to an edge). Pressure drops can be balanced by making local adjustments in the part's wall thickness. Local increases in wall thickness (to promote flow) are known as flow leaders or internal runners, while wall thickness reductions (to hinder flow) are known as flow restrictors. On a box-shaped molding, such as that shown in Fig. 2.29, one could thicken the diagonal areas extending towards the corners of the part to promote flow to these areas of maximum flow length. This situation is one of the few instances where a designer purposely deviates from the rule of maintaining a uniform wall thickness. The changes in wall thickness are sometimes very subtle. Computer aided mold filling analyses are useful when designing flow leaders/restrictors, as are the pressure drop calculations outlined earlier in this section (treat the various flow lengths as individual strips of finite width and adjust thickness in an effort to balance the pressure drop). Flow leaders extend from the gate towards the hard to fill sections, while flow restrictors (or dams) can be placed along sections of the cavity that are more easily filled. These wall thickness changes are generally incorporated into non-appearance or less visible surfaces of the molding. The flow leaders or restrictors should be blended and tapered into the part wall to minimize complications created by the introduction of the non-uniform wall thickness (e.g., stress concentration or differential cooling and shrinkage effects). Ribs that are commonly used to stiffen plastic parts can also be used as flow leaders when properly sized and positioned. The melt flow pattern within the cavity will also be influenced by the mold cooling circuit design. Warmer tool temperatures will tend to promote flow.

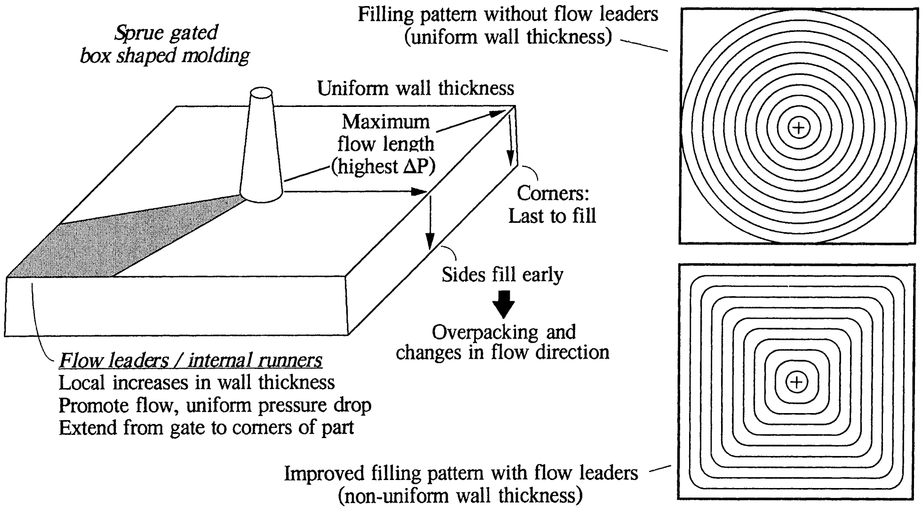

Figure 2.29 Flow leaders or flow restrictors can be used to alter the mold filling pattern in an effort to achieve more balance mold filling

The mold filling pattern for the part shown in Fig. 2.28 could be modified using flow leaders or restrictors. The part shown in Fig. 2.30 was produced using three gates and diagonal flow leaders. The properly designed flow leaders eliminate underflow effects and ensure uniform packing, resulting in a higher quality part.

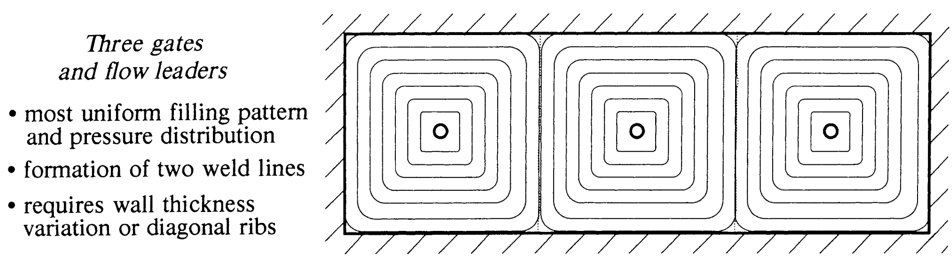

Figure 2.30 A uniform filling pattern is achieved when three gates and diagonal flow leaders are used

However, there are practical limits associated with the use of flow leaders/restrictors. For example, it would be difficult to balance flow for the part shown in Fig. 2.27 produced using one gate due to the degree of imbalance.

Flow Hesitation and Race-Tracking Many plastic parts are in fact designed with variable wall thicknesses. This practice should generally be avoided, but sometimes variable wall thicknesses cannot be avoided. Variable wall thicknesses lead to a variety of shrinkage related

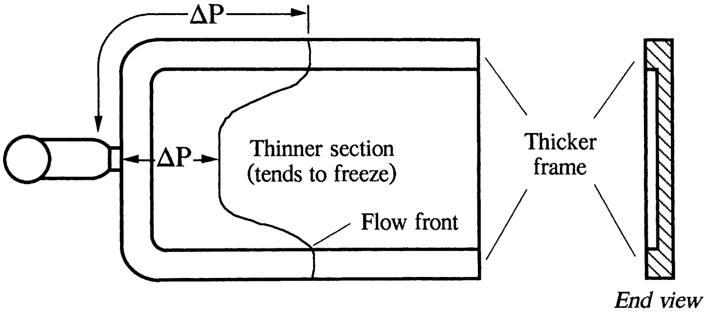

Figure 2.31 When plastic parts have both thick and thin wall sections, the melt tends to flow preferentially through the thicker sections communicating with the gate because the melt will follow the path of least resistance

problems (as discussed later in the chapter), and can lead to a variety of difficulties during mold filling [17]. This point is demonstrated in Fig. 2.31.

The part in Fig. 2.31 has a relatively thin central section surrounded by a thicker frame or rim. The designer has placed the gate along the thicker rim so that the thick section can be packed even if the thin section freezes. Unfortunately, during mold filling, the melt tends to "race-track" or "picture-frame" around the thick rim because the melt follows the path of least resistance. The melt in the central thinner region will tend to "hesitate" until the thicker sections are full, at which time it begins to flow again. This can lead to problems with high residual stress, poor surface appearance, gas trapping, and short shots in extreme cases. The thin section is acting like an unwanted flow restrictor. The simplest way to avoid this situation is to avoid the use of variable wall thicknesses. When variable wall thicknesses must be used, the variations should be kept to a minimum. Gating the part in the thinner sections can minimize the filling problems, but may lead to packing problems in the thicker section. A computer aided filling analysis is recommended for parts with variable wall thickness so that flow hesitation or race-tracking problems can be detected in advance. If the problem does arise, the gating schemes can be altered or wall thicknesses can be adjusted until a more balanced flow pattern is achieved.

Multi-Cavity vs. Family Molds Many plastic products actually consist of a series of injection molded parts that must be assembled in a secondary manufacturing operation or by the consumer. When the individual parts that make up the product are produced from different plastic materials, a series of injection molds (or interchangeable insert sets) are generally constructed to produce the individual components. Alternatively, for prototype or low production situations, a single multi-cavity family mold with runner shut-offs could be used to mold the individual parts one at a time. If, however, all of the parts that make up the product are produced from the same plastic material, it may be possible to produce all or some of the components in one shot, using a family mold.

In most cases, a series of single-cavity or balanced higher production, multi-cavity molds is preferable to the family mold option. However, when production volumes are low, a family

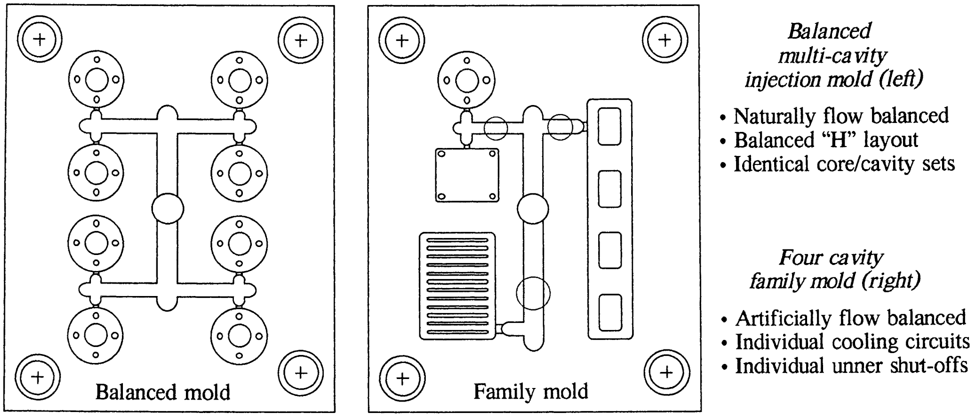

Figure 2.32 Multi-cavity and family molds should be flow balanced to avoid flow hesitation or overpacking problems. Runner shut-offs and additional cooling circuit control can assist the process engineer once the mold reaches the production floor

mold, such as the one shown in Fig. 2.32, is often a more economical tooling option. It is important that family molds are designed in such a way that each individual cavity fills at the same time (as with a naturally balanced multi-cavity tool). Flow balancing for the family mold can be accomplished with proper cavity layout and by adjusting runner lengths and diameters in an effort to equalize the pressure drop in each flow branch. Once constructed, it can be very difficult to work with a family mold during production, especially when the tool has not been properly flow-balanced. For example, one of the parts may be overpacked and oversized, while another is undersized. Changing molding conditions to bring one part into dimensional specification will most likely magnify the problem for the other part. When parts must be produced in a family mold, it is important to design the tool in such a way that each section of the mold can have its own cooling circuit. In this way, individual mold temperature adjustments can be made for each cavity, giving process engineers some additional level of control. It may also be beneficial to include runner shut-offs so that parts can be produced individually as a last resort. The runner shut-offs can also provide a location where flow restrictors are easily inserted. There are a number of disadvantages associated with family molds, but there are also some advantages. For example, color matching problems are effectively eliminated with family molds because all parts that make up the product assembly can be molded at the same time (i. e., same machine and same heat/shear history). Parts handling can also be minimized, especially when the entire shot can be shipped as a unit for consumer assembly.

Gating from Thick to Thin When injection molded plastic parts do have variable wall thicknesses, it is generally good practice to gate into the thickest section of the molding, as shown in Fig. 2.33. The thicker section of the molding requires more packing/shrinkage compensation and should therefore be located closest to the gate. When this is not done, a thin section located between the gate and the thicker section can freeze off and the ability to pack the

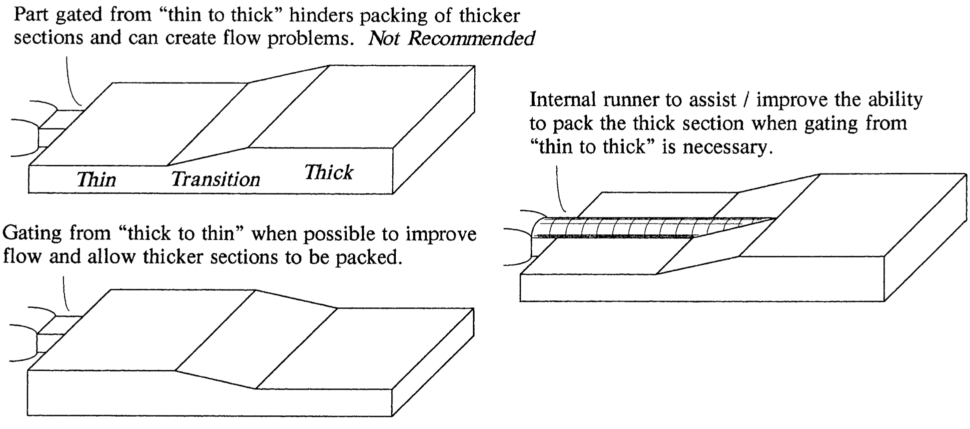

Figure 2.33 Parts with variable wall thicknesses should be gated at the thicker sections whenever possible to reduce the potential for sink marks or voids. If the part must be gated from "thin to thick", internal runners (possibly ribs) can be added to facilitate packing of the thicker sections

thicker section is lost. It can also be difficult to achieve good surface finishes for parts gated from thin to thick, as the melt front tends to cool and jet as it exits the thinner region. If for some other reason the gate must be positioned in a thin section of the molding, an internal runner or modified rib can be used to keep a flow channel open during the packing and holding phases of the molding process, as shown in Fig. 2.33 [18].

While gating into the thicker wall sections of a plastic part does provide control over packing, it can lead to other molding problems, such as "jetting" [19]. Jetting can occur when gating into a thick, open cavity. When jetting occurs, the melt tends to stream into the deep cavity, rather than develop as a fountain flow front. If jetting does occur, the molded part will have a relatively poor surface appearance. The rope-like jet of polymer cools during the early stages of the mold filling process and does not weld together properly. Perhaps more importantly, the mechanical and chemical properties of the parts are also likely to suffer when jetting occurs.

Jetting effects can be minimized with proper gate design. For example, short gate land lengths promote expansion of the melt as it enters the cavity due to elastic/memory effects (an extrusion die designer would do just the opposite, i. e., use long land lengths for an extrusion die to minimize die swell-related dimensional changes as the extrudate leaves the die). Large gates, especially fan gates, and tab gates can be used to minimize the potential for jetting. Gating into some type of flow obstruction (e. g., core pin, etc.) will also help the melt flow front develop, thereby minimizing the potential for jetting.

Summary: Consider the disc shaped moldings shown in Fig. 2.36 (a to e). The moldings have a thin central disc section surrounded by a relatively thick rim. There are a number of possible

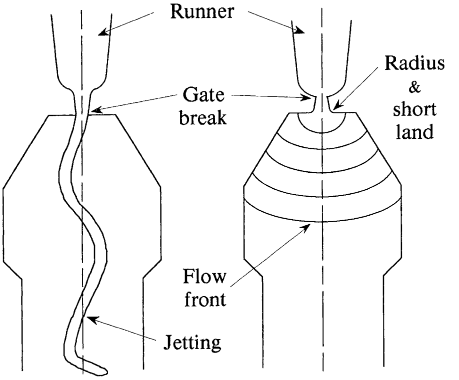

Figure 2.34 Jetting can occur when gating into a thick, open cavity. The potential for jetting can be reduced with proper gate design or by gating into an obstruction. Velocity profiling during the injection phase of the process can also be used to promote melt flow front formation as the melt enters the cavity

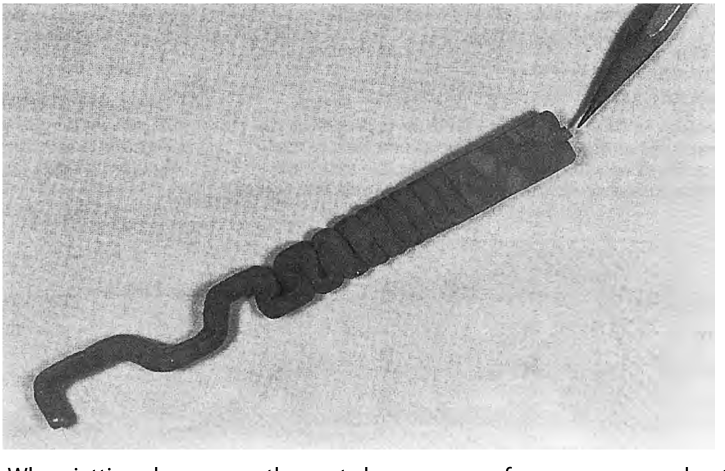

Figure 2.35 When jetting does occur, the parts have poor surface appearance due to improper welding of the jetting melt as the cavity fills. Jetting can also result in a reduction in mechanical performance

gating schemes that could be used for a plastic part with this general type of geometry. Each of these gating schemes offers its own relative advantages and limitations.

- *Top center gating:* Central gating offers the advantage of balanced flow, uniform venting at the parting line, and no weld lines. However, the part is gated from thin to thick, and it is likely that the thicker section would not be fully packed, resulting in sink marks or shrinkage voids.

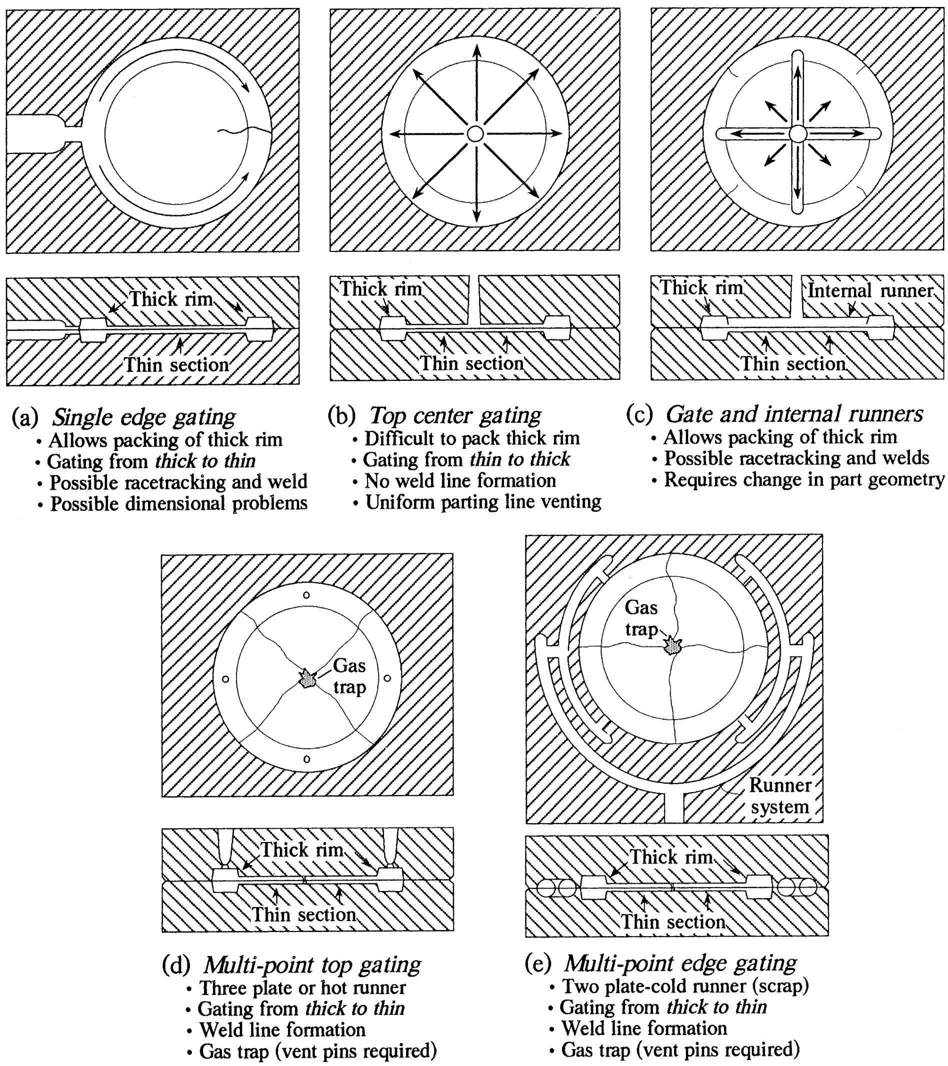

Figure 2.36 The disc-like part has a thick rim surrounding a thinner central region. Selecting a gating scheme is complicated by the fact that the part has a non-uniform wall thickness. Each of the five options shown has its own relative advantages and limitations

- *Edge gating:* Gating into the edge of the part would facilitate packing of the thick section; however, it is likely that the melt would race-track around the outer rim. This could result in a weld line and the potential for a gas trap or short shot due to flow hesitation. The "roundness" of the part would also be in question with this gating scheme.

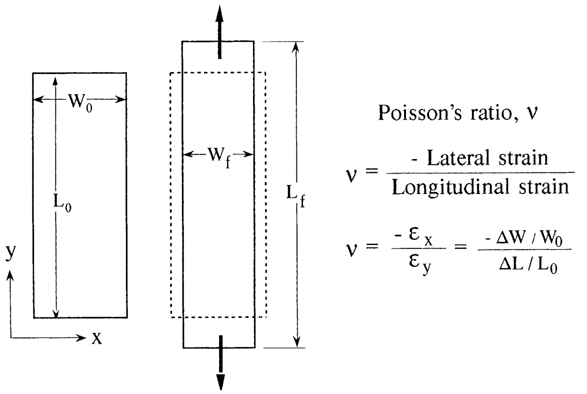

Figure 3.18 Poisson's ratio is a measure of the lateral to longitudinal strain values for a material. The value is used in a variety of design equations and to convert between the material's shear modulus and tensile/compressive modulus

Table 3.1 Typical values of Poisson's ratio [6]

Material	Range of Poisson's Ratio
Aluminum	0.33
Carbon steel	0.29
Ideal rubber	0.50
Neat thermoplastic	0.20–0.40
Reinforced/filled thermoplastic	0.10–0.40
Structural foam	0.30–0.40

Like the elastic and shear modulus values, Poisson's ratio changes with variables such as temperature, strain or stress level, and strain rate.

Poisson's ratio values are used to relate elastic and shear modulus values and are required for many structural design calculations.

3.4.3 Long Term Mechanical Properties: Creep

The mechanical behavior of a polymeric material is influenced by a number of factors including time, stress or strain levels, and environmental factors, such as temperature and moisture content (for hygroscopic polymers). The set of short-term stress–strain curves given in Fig. 3.11 shows that at higher loading or strain rates, plastic materials appear to be more rigid and brittle. On the other hand, at lower rates of loading or strain, plastic materials appear to be more flexible or ductile due to viscous effects. These viscous effects are a particular concern in applications where loads are applied for extended periods of time (i.e., static loads). It is not unusual for plastic parts to be subjected to continuous loading (either service loads and/or the part's own weight) or loading for relatively long periods of time (i.e., days, weeks,

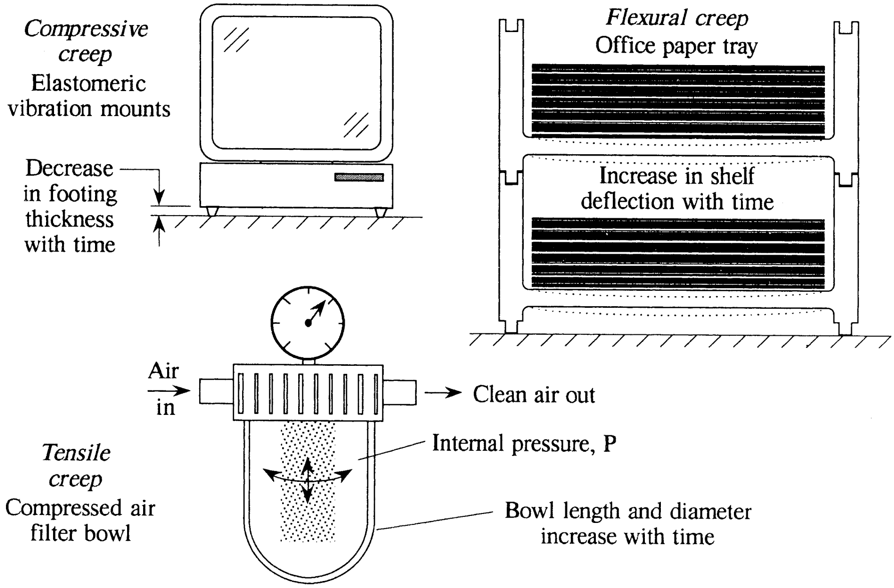

Figure 3.19 Typical applications where molded plastic parts are subject to constant stress for extended periods of time (i. e., creep applications)

years). When parts are loaded in this manner, they will exhibit both initial elastic deformation or strain due to the applied load, but they will also exhibit a continuous (time dependent) increase in deformation or strain due to viscous or cold flow (i. e., creep). This phenomenon has nothing to due with aging effects (e.g., oxidation, etc.) which must be given separate consideration for longer-term applications. The parts shown in Fig. 3.19 are all subject to long term loading (or stresses) and as such must be designed with considerations for creep deformation.

In order to design parts that are subject to long term loading, designers must obtain and utilize creep data in an effort to ensure that the parts do not rupture, yield, craze. or simply deform excessively over their service life (service life *must* be specified during the initial stage of design since creep deformations are time dependent). The creep data used in design must correlate with the type of stress and environmental conditions that the part is subjected to during service. The time and temperature dependent creep modulus, $E_c(t, T)$, of a polymer is given by:

$$E_c(t, T) = \frac{\sigma_o}{\varepsilon(t, T)} \tag{3.6}$$

Where σ_o is a constant stress and $\varepsilon(t, T)$ is the time- and temperature-dependent strain.

Unfortunately, service load magnitudes, durations, and environmental conditions can be difficult to predict over the long term, and it maybe difficult to find test data which correlate exactly with the end-use application, especially when loads are semi-continuous and recovery must

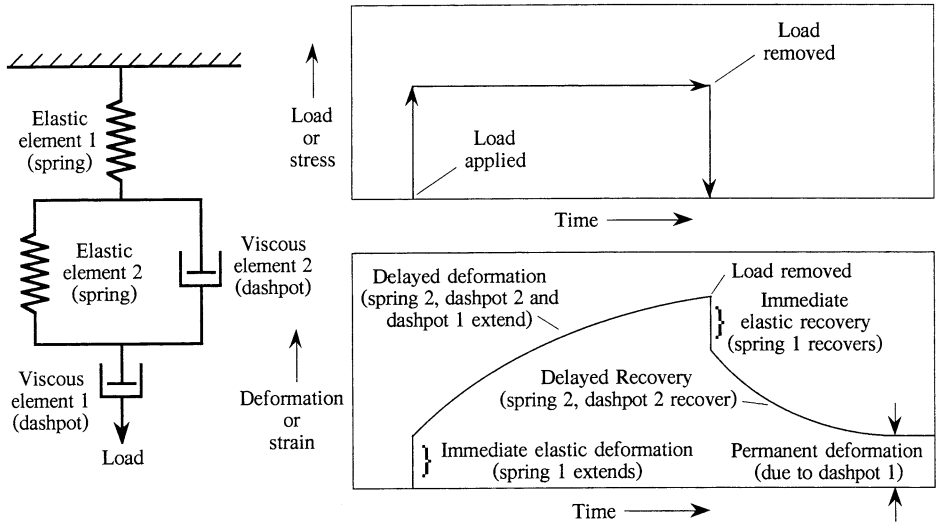

Figure 3.20 Spring (elastic element) and dashpots (viscous elements) are commonly used to describe the mechanical behavior of plastic materials

be considered. This can make it difficult to accurately estimate the structural performance of a part subject to creep loading, and it is often best to assume continuous loading at the highest anticipated service temperature for safety.

The creep behavior of a plastic material is often modeled using spring (elastic element) and dashpot (viscous element) analogies. The model shown in Fig. 3.20 can be used to describe the general creep behavior of a plastic material subject to a tensile load. The figure shows Voight-Kelvin and Maxwell Models in series with one another to create a four parameter model.

When a tensile load is applied to the spring/dashpot model, elastic element #1 extends instantaneously, resulting in an immediate elastic deformation (IED) inversely proportional to the stiffness of the spring and proportional to the magnitude of the load (this results in stored energy). Elastic element #2 is unable to extend immediately because it is constrained by a viscous dashpot that cannot react instantaneously. The load then causes further deformation with time as dashpot #1, dashpot #2, and spring #2 extend. This represents the time dependent creep or delayed deformation (DD). At some point of extension, spring #2 (hence dashpot #2) will reach equilibrium, but dashpot #1 will continue to extend with time of load application. When the load is ultimately removed, the stored energy in spring #1 will cause an immediate elastic recovery (IER), followed by a delayed recovery (DR) associated with the retraction of spring #2, hindered by dashpot #2. The extension associated with dashpot #1 is irrecoverable and represents the permanent deformation or set (PD). While the actual creep and recovery behavior of most polymeric materials is more complex than this simple analogy, it does provide insight into the general concept of viscoelastic behavior.

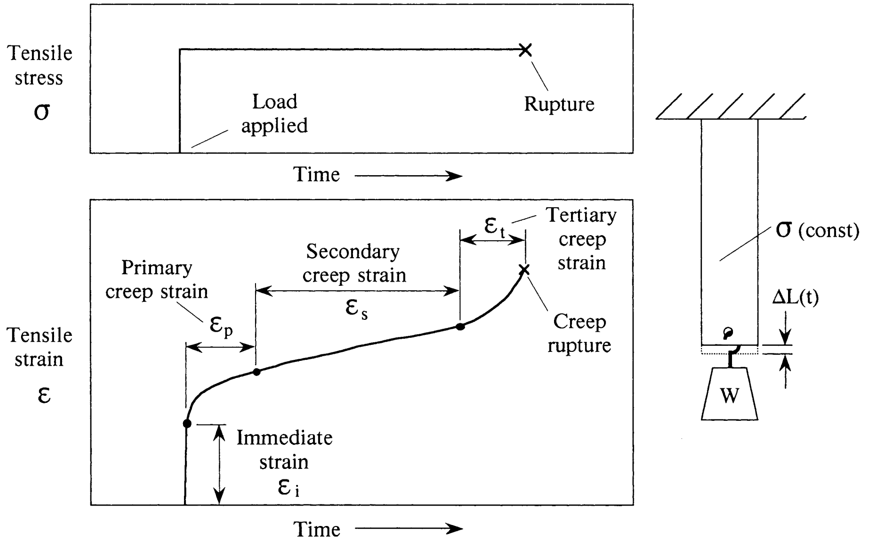

Figure 3.21 The strain response of a plastic material to an imposed stress can involve both elastic strain and creep strain

In practice, when plastic materials are stressed, an immediate elastic deformation is observed, followed by primary, secondary, and tertiary creep [8]. Primary creep is associated with a decreasing creep rate with time and is at least partially recoverable. Secondary creep occurs at a constant rate with time, while tertiary creep occurs at an increasing creep rate with time just before creep rupture (Fig. 3.21). The rate of creep is material-, stress-, and temperature-dependent, as are the creep rupture strain values. It should be noted here that rupture (or yielding) will occur at stresses below the corresponding short-term test breaking stress values. Creep rupture occurs at relatively shorter times for higher stresses and relatively longer times for lower stresses.

Creep Testing: Material manufacturers generate creep data by subjecting molded test specimens (prepared by the injection or compression molding process) to different stress levels (typically four or more different stress values), and monitoring the change in length or strain as a function of time (Fig. 3.22). Tests are commonly conducted at a series of constant temperature environments that are typical use temperatures for the material under consideration. Tests can be conducted in tension, compression, bending, or shear. Ideally, tests should be run for many years in order to truly quantify the creep and creep rupture behavior of the material; however, due to practical constraints, tests are commonly run for shorter periods of time. It is important for designers to determine whether the creep data they are working with are actual experimental data or extrapolated data (from a shorter-term test). It is possible to extrapolate creep and creep rupture curves; however, it should be done with caution and should generally be limited to one logarithmic decade [9].

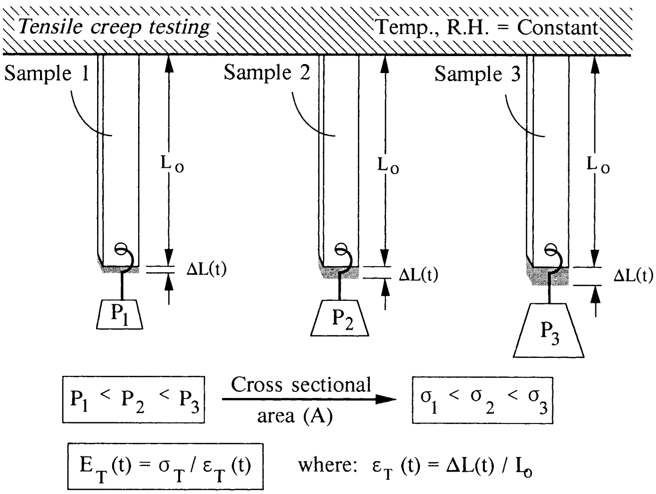

Figure 3.22 Creep data is generated by subjecting molded samples to a series of loads, or stresses and monitoring the change in length, or strain, over time (tension, compression, bending, or shear)

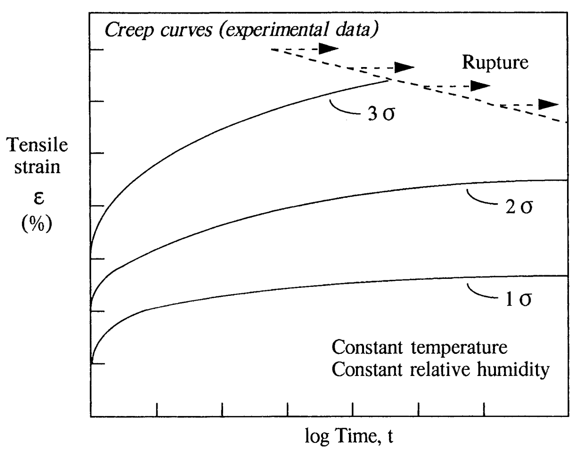

Figure 3.23 The experimental data from a creep test is used to plot strain vs. log time curves at various stress levels (at constant temperature and relative humidity)

The experimental creep data is typically plotted as a graph indicating strain as a function of log time, at constant temperature/relative humidity and various stress levels, to produce a "creep curve" (Fig. 3.23). The slope of the creep curve is an indication of the stress-related dimensional stability of the plastic material. Higher stress levels cause an increase in creep as do higher temperatures.

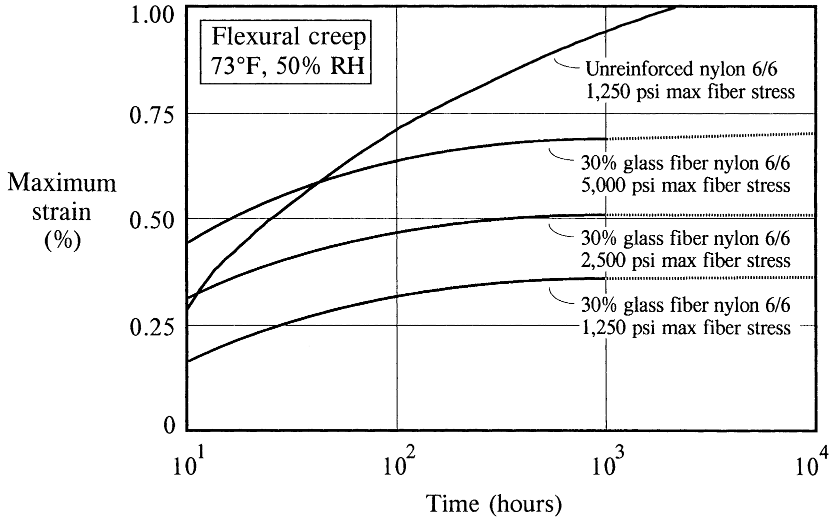

Figure 3.24 The creep resistance of a polymer is improved significantly with the addition of reinforcing fiber

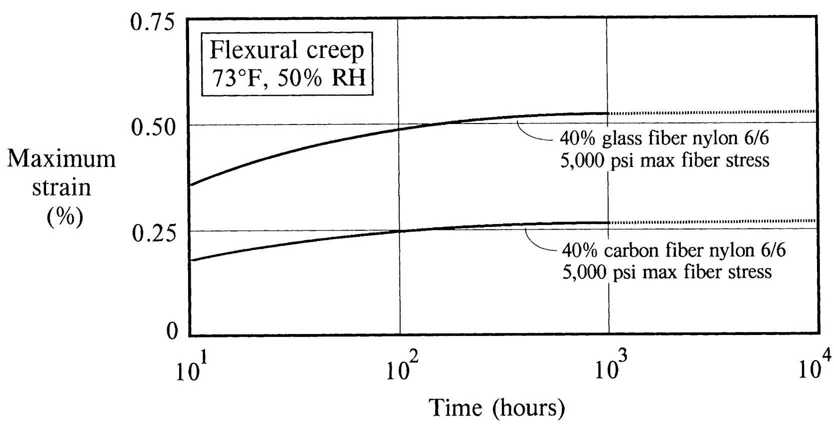

Figure 3.25 Fibers that are commonly used to enhance creep resistance of a polymer include glass and carbon fibers

The rate of creep for filled and fiber reinforced polymers is significantly lower than that of unfilled materials, provided appropriate coupling agents are used. Figure 3.24 shows that the creep strain values for glass fiber reinforced nylon are significantly lower than those of neat nylon 6/6, even when the reinforced material is subjected to higher stress levels. The resistance to creep can be enhanced even further when graphite fiber reinforcements are used, as shown in Fig. 3.25 [10]. It should be noted here that the effects of weld lines and fiber orientation on creep behavior should be taken into consideration when working with fiber reinforced polymer grades. During creep testing, it is also common to inspect samples for yielding, rupture, stress cracking, crazing, and stress whitening. Creep rupture (or yield) test data are typically plotted to produce a set of curves at various temperatures, indicating the failure or yield stress as a function of log time, as shown in Fig. 3.26.

Creep rupture can occur by either ductile or brittle failure modes, which are typically distinguished by macroscopic appearance. Ductile fractures involve some type of gross plastic deformation, such as yielding, necking, or shear, all of which involve shape changes or distortion. Brittle fractures on the other hand do not involve gross deformation, but only very localized plastic deformation [11].

Crazing: In many polymers, crack initiation is preceded by craze formation. Crazes appear as crack-like planar defects; however, they contain an interpenetrating network of voids among highly drawn polymer fibrils bridging the craze faces. Crazing or craze yielding is a cavitation process that is accompanied by a volume increase, as shown in Fig. 3.27 [11].

Crazes begin with micro-void formation under the action of a tensile stress. Once initiated, these voids increase in size and begin to elongate along the direction of the principle tensile stress, forming fibrils that bridge the craze faces. While the appearance of crazes does not in and of itself constitute failure under static loading conditions, crazes can eventually lead to

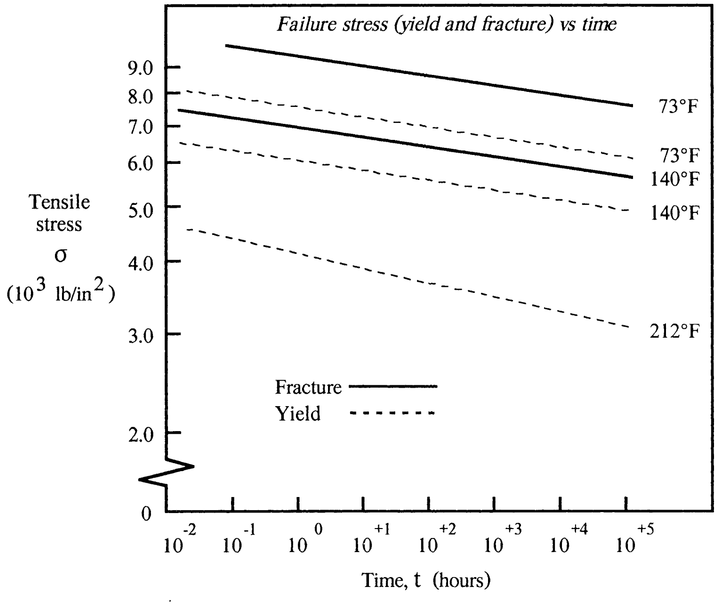

Figure 3.26 The stress at which a plastic part will yield or rupture in creep is dependent on the duration of creep loading and temperature. Creep yield and rupture strength values are shown for a polycarbonate at various temperatures

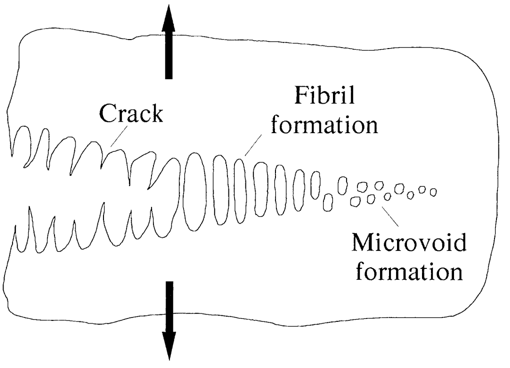

Figure 3.27 Micro-voids and crazes can eventually lead to cracking and brittle failure

brittle failure or cracks, and are a particular concern in applications where there is the potential for additional impact loading, dynamic loading, or aggressive chemical environments.

Crazing is a particular problem for many materials when they are stressed (particularly surface tensile stresses) in the presence of aggressive chemicals. Environmental stress cracking and crazing (ESCC) can occur when plastic parts are stressed (internal/residual molding stresses or externally imposed stress) in a chemical environment, even when the stresses are relatively low (Fig. 3.28). It is the combination of the stress and the chemical that lead to crazing and ultimately to failure (a kind of negative synergy). Even water or mild detergents can have a very negative impact on the mechanical performance of a plastic part (with some materials) subjected to mechanical stress [12].

Stress Whitening: Stress whitening is a general term used to describe phenomena that result in clouding, foggy, or whitened appearances in transparent or translucent polymers. The

Figure 3.28 Photo showing craze formation on an acrylic part

whitening is generally the result of micro-void formation caused by delamination with fillers or fibers, or by localized failure around inclusions, such as rubber particles or other impact modifiers [10].

Creep Curves: Creep curves, such as those shown in Figs. 3.23–3.25, are graphical representations of the experimental data obtained from a creep test. The same creep data can be plotted in other ways that are more convenient to use for design purposes.

Creep curves, such as the one shown in Fig. 3.29, are commonly sectioned at various constant time values (typically 1 hour, 10 hours, 100 hours, 1000 hours, etc.) to obtain stress–strain data at those specific time intervals. The data are re-plotted in the form of an isochronous stress–strain curve, as shown in Fig. 3.30 [12]. The curves are used in place of short-term stress–strain curves when designing for applications involving long-term static loading.

Isochronous stress–strain curves are generally available at a series of temperatures so that designers can consider the effects of both time and temperature on the apparent or creep modulus of the polymer. The apparent creep modulus values are commonly used in place of the Young's Modulus value in classical design equations to predict the strains or deflections associated with long term loading. It should be noted that the apparent modulus value varies with time, temperature, and stress level. The isochronous stress–strain curves in Figs. 3.30–3.32 also indicate the craze limits or onset of crazing for the polymer at various temperatures. The stress (or strain) level at the point where the craze limit line (dash line) intersects with an isochronous curve is the stress (or strain) level associated with the onset of crazing at that particular time. For example, the isochronous stress–strain curve for the polycarbonate at 140 °F/50 % RH shown in Fig. 3.31 indicates that crazes will appear in about 10 hours at a stress level of 4 000 psi, while it will take approximately 10 000 hours for the crazes to appear

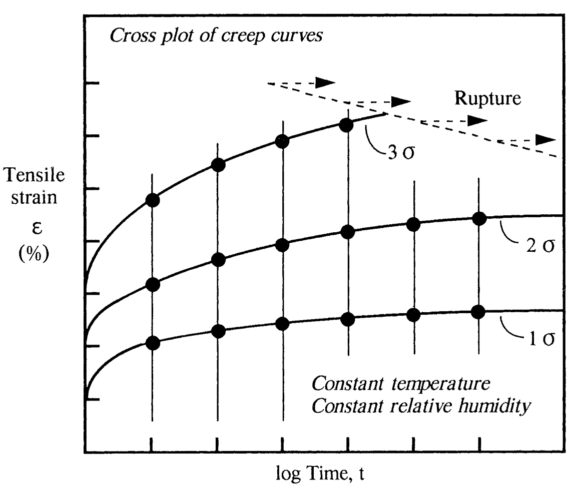

Figure 3.29 Creep curves are commonly sectioned at standard time values (1 hour, 10 hours, 100 hours, 1,000 hours, etc.) to generate data for isochronous stress–strain

and DFER concepts are in fact "fully compatible" with the more commonly applied *Design for Manufacturability* (DFM) philosophy. For example, reducing the number of components and different thermoplastic materials that make up a product will usually reduce the cost of manufacturing the product and enhance its recyclability at the very same time.

Incorporation of recycle content into new products can be another very important aspect of environmentally friendly design. However, there are a number of important design issues that are associated with the use of either post-industrial or post-consumer recycled thermoplastics in new products relative to those products made from virgin thermoplastics. Designers of thermoplastic parts that are fully produced from recycled thermoplastics, or that incorporate a percentage of recycled thermoplastic (i. e., contain plastic parts having recycle content) have "additional responsibility" and *must* carefully plan for the use of the recycled thermoplastics right from the start. If recycled thermoplastics are used, the designer should consider a number of sourcing, processability, and performance related issues as outlined in this chapter. Many of these issues should be given "more than usual" attention by the designer when recycled thermoplastic are utilized. Like their virgin counterparts, recycled thermoplastics can be used successfully in many (but not all) end use applications, if their use is carefully considered early in the design stages of product development right through to manufacturing. A number of the important design issues related to *Design for Enhanced Recyclability* and *Design for Recycled Thermoplastic Content* are discussed in the remaining sections of this chapter.

7.2 Designing Thermoplastic Products with Enhanced Recyclability

The "recyclability" of any product is determined by a large number of material and design related factors. Product designers *do not* determine whether or not the materials that make up their product will be recycled. However, product designers do (to a very large extent) determine the "ease" of recycling their product. Thermoplastic products that have been designed with enhanced recyclability in mind are at least in theory more likely to be recycled at the end of their service life compared to those that have not been designed with recycling in mind. The "ease" of recycling, while difficult to quantify exactly, is very closely related to the "economics" of recycling. It is likely that both the "quality" and the "quantity" of recycled thermoplastics available for reuse as a secondary material would increase, if designers of plastic products considered recycling issues when they make their various design decisions throughout the course of the product development process. In past years, many designers have not treated product recyclability as a very high priority in their decision making process, if at all. In fairness, the "primary" responsibility of a product designer is to ensure that the product they are designing will meet the end use requirements associated with the application. The product must first and foremost be "fit for its purpose". This requires trade-offs between many competing design issues, only one of which is the inherent recyclability of the product. Recycling related issues have typically been treated as secondary issues, and in some cases are not ever considered at the design stage of product development. However, many product designers are now beginning to realize how much impact they as individuals have on the recyclability of a new product. Even relatively minor design or material changes can have a significant positive or negative impact on the recyclability of an item.

Many of the practical developments associated with the *Design for Enhanced Recyclability* philosophy have been both pioneered and very successfully implemented by the thermoplastic bottle or rigid thermoplastic container packaging industries. Organizations such as the Association of Postconsumer Plastic Recyclers [9], and the National Association for PET Container Resources [10] have worked closely with container designers, container recyclers, and end users of the recycled thermoplastics (obtained from the containers) in an effort to enhance both the quality and the quantity of recycled thermoplastics derived from post-consumer containers. The automotive, consumer electronics, building construction, and other thermoplastic industry market sectors have been following in the footsteps of the thermoplastic packaging industry in an effort to enhance recycling rates for their products. For example American Chemistry Council has developed guidelines for the design of Information and Technology Equipment [11]. Generally speaking, industries face more problems in implementing the recycling of thermoplastic components for their more durable goods due to a variety of factors, including the greater variety of materials utilized in manufacturing their products, lack of standardized infrastructure, and the generally more complex construction of most durable goods.

That said, designers of literally any plastic product should recognize that the design decisions they make along the way will impact the inherent recyclability of the product in many different ways.

The "materials of construction" for a product are central to the recyclability of the product in many respects. It is also important for designers to work within the bounds of the existing recycling infrastructures and practices whenever possible, avoiding the need for new recycling technology developments. Designs that simplify disassembly and reduce the potential for contamination are critical for multi-material, multi-component products. A number of the "concepts" or "design guidelines" that relate to the recyclability of thermoplastic products are listed in Table 7.1. Each DFER concept is then discussed in more detail. These guidelines are not necessarily universally accepted nor are they appropriate for all applications. The relative importance of each DFER concept varies from product application to product application. The concepts are presented here in good faith, based upon the experience of the author.

7.2.1 Design for Existing Recycling Infrastructure

All thermoplastic items are recyclable in theory. However, far too few thermoplastic items are recycled in practice. One of the many reasons that many thermoplastic items are not routinely recycled is that they have not been designed to be compatible with the existing recycling infrastructure. The concept of *Designing for the Existing Recycling Infrastructure* should be applied whenever possible, which can be difficult due to a lack of infrastructure. This is a perfect example of the chicken and egg scenario. The chances of a thermoplastic item being recycled are far better if its recycling can be done using an existing and proven commercial recycling infrastructure. Recycling is far less likely, if new technologies or materials handling practices are required in order to achieve that end. There are many possible

Table 7.1 Some *Design for Enhanced Recyclability* (DFER) concepts for thermoplastic parts or products

Concept 1. Design thermoplastic products so that they can be recycled using existing and proven recycling infrastructures and technologies.

Concept 2. The thermoplastic parts that make up a product and its thermoplastic packaging should be marked with an imprinted or a molded-in material identification code (size permitting).

Concept 3. Single component, single material thermoplastic items are most easily recycled. Multi-component products should minimize the number of parts and their materials of construction.

Concept 4. Design for simplified disassembly for multi-component, multi-material product applications where component de-manufacturing and material segregation will take place prior to granulation.

Concept 5. Design for easier granule separation for multi-component, multi-material product applications where material segregation will occur after commingled or bulk granulation.

Concept 6. If disassembly of a multi-material product for recycling is not technically or economically feasible, the materials of construction should be compatible with one another for commingled recycling.

Concept 7. Use thermoplastics that have good inherent recyclability and economic value as a recycled material.

Concept 8. Minimize the use of specialty additives that limit secondary markets. The use of natural (unpigmented) thermoplastics is desirable. When pigmented materials are used, lighter, standardized color dyes or pigments are preferred.

Concept 9. Molded-in labeling is the preferred method of labeling. Adhesive free thermoplastic labels, such as stretch film labels, are preferred to those requiring adhesives. Compatible thermoplastic labels are an option. Direct printing is another labeling alternative, especially for pigmented thermoplastic parts. Any label adhesives should be warm-water soluble or alternatively compatible with the substrate thermoplastic.

Concept 10. Surface coatings, such as paints, platings, EMI/RF coatings, barrier coatings, or hard coatings, should be avoided whenever possible. Removing the coating contamination prior to recycling the substrate parts can be technically difficult and expensive.

Concept 11. Scrapless manufacturing processes, such as hot runner injection molding, are preferable to those that generate manufacturing waste, such as cold runner injection molding.

material and design implications related to this concept of designing for the existing recycling infrastructure (depending on the specific application). However, there are critical universal features associated with the concept. First, the designer of a new product should determine which recycling technology(s) might be appropriate for their new product. Once this has been done, the designer can spend time talking/meeting with the thermoplastic recycler proactively, in an attempt to make the product more recyclable. Every single decision that a

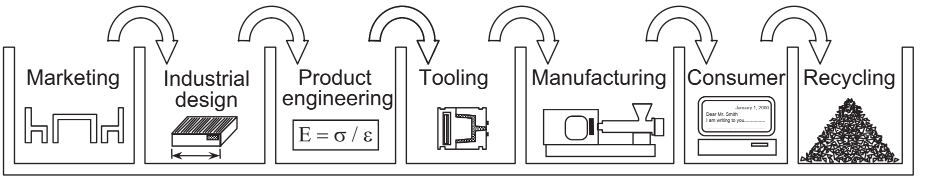

Figure 7.1 The series- or "Over the Wall"-approach to product development is not the optimum way to develop a new product. Design changes associated with manufacturing or recycling concerns can be difficult to implement, if they are not detected until late in the product development cycle. Product recycling may be impossible or impractical, if a recycler is not consulted as part of the design process

designer makes during the product development process can impact the recyclability of the product. No one knows more about thermoplastic recycling than the recyclers themselves.

This situation shows many analogies to that of *Design for Manufacturability* (DFM). For example, it is best if the designer of a new injection molded part discusses manufacturing issues with both processor (e.g., molder) or tool/die designer early on in the product development cycle. The molders and tool makers can provide information on parting line locations, gating, draft angles, and in general can help the designer develop a part that is more easily molded and usually less expensive to manufacture. If the designer does not contact the molder until after the part has been designed, the process is known as the series- or "Over the Wall"-approach to product development. With this series-approach to design, manufacturing related design changes are not detected until late in the design cycle when design changes can be difficult to implement (e.g., other mating parts are affected by the changes). However, if the part designer discusses these sorts of issues with the molder or tool designer as the part design is evolving, the design changes are easier to implement. This design process or methodology is known as parallel or "Concurrent Engineering". The latter design process tends to both speed up the product development cycle and results in a product that offers a better balance of aesthetics, cost, performance, and manufacturability.

Enhancing the recyclability of a product is analogous to enhancing its manufacturability. If the designers of a new product contact the recyclers early on in the product development process, they are simply extending the concept of concurrent engineering deeper into the life cycle of the new product. The recycler can let the designer know, how design decisions related to material selection, assembly, decorating, coding, labeling and the like will impact the recyclability of the product. This practice does not necessarily improve the recyclability of the product (in all cases) as product designers are concerned with many issues, only one of which is the product's recyclability. However, it does give the designer the required recycling "information" on which they can base their design decisions. All other factors being equal (or close to equal), a more recyclable design is clearly the more logical choice.

The concept of "Designing for the Existing Recycling Infrastructure" is best illustrated using the example of thermoplastic bottles. The Association of Postconsumer Plastic Recyclers has developed a set of recommended design guidelines for plastic bottle designers [9]. The guidelines have been developed so that designers of "new" thermoplastic bottles or containers can

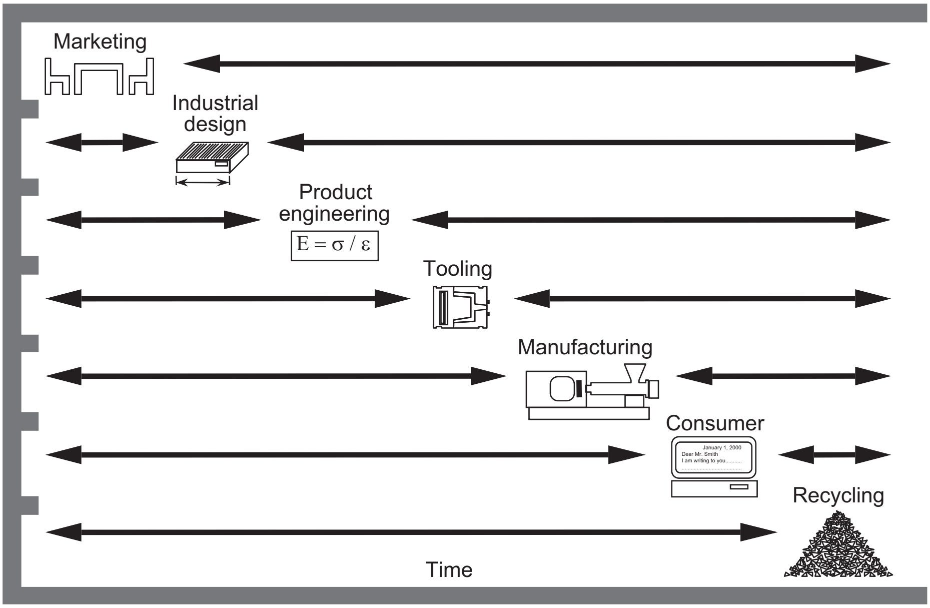

Figure 7.2 The "Concurrent Engineering" process is a more parallel product development process conducted by a more interactive team. This tends to both speed up the product development cycle, and result in a product that offers a better balance of aesthetics, cost, performance, manufacturability, and recyclability (if the design team seeks the advice of recyclers throughout the product development process)

make these packages more compatible with the existing recycling infrastructure (to make these containers more recyclable). The recycling guide gives a series of recommendations associated with design variables, such as materials selection, attachments, closures, safety seals, color, labels, adhesives, decorating, and coatings. If container designers follow these recommended practices, the end result will be a container that is recyclable with the existing recycling infrastructure. While these design guidelines have been developed specifically for plastic bottles or containers, many of the concepts presented are applicable to other thermoplastic products. Companies that specialize in the recycling of industrial and post consumer waste can provide input on how even small design or material changes can either enhance of complicate recycling [12].

7.2.2 Standard Material Identification and Marking Systems

There are a number of different material marking/coding systems that should and sometimes must be used to identify the material from which a plastic item or component is manufactured [5, 13–15] These coded markings or material designations are either molded into the plastic part or may be printed onto the surface of the part. The markings are appropriate for plastic parts and packaging items that are physically large enough to permit marking. The purpose

>HDPE<

Figure 7.3 There are a number of different thermoplastic "material of construction" marking protocols in use today. Designers must determine which coding protocol is most appropriate for their application, the method of marking and the location of the marking. The chasing arrow SPI material coding system [14] was developed to enhance the recycling rates for plastic bottles and containers. The ASTM marking code [13] for the same is shown on the right

of providing the material code is not necessarily to imply inherent recyclability, but rather to provide information that can assist consumers and recyclers with decisions regarding the disposition of an item once it has reached the end of its service life. Recycling is but one of these options. Designers of thermoplastic components or items must determine

- which marking protocol is most appropriate for their application,
- which method of marking is most suitable, and
- which locations on an item are most appropriate for marking.

Plastic "material of construction" coded markings are a requirement for most ecolabel certifications and are required by law in some packaging applications. In many other cases, the markings are applied voluntarily. The coding systems are not universal. For example, the SPI code for HDPE differs from SAE's or ASTM's, as shown in Fig. 7.3 and therefore an HDPE windshield washer reservoir would have a different mark than a milk bottle. More standardization might help increase the rates of recycling for plastics.

The coded markings are not always used by consumers or recyclers, but there are few negative effects associated with their use. There is the obvious issue as to how the code affects

Table 7.2 ASTM D1972 generic marking system for plastics products
Abbreviated terms from ASTM D1600: ›Plastic and additive abbreviations‹

Product/Thermoplastic Characteristic	Example Thermoplastic Formulation	Example Product Marking*
Single "neat" thermoplastic	Unmodified ABS	›ABS‹
Thermoplastic "blend or alloy"	An ABS/polycarbonate blend	›ABS + PC‹
Thermoplastic with "one" additive used at > 1 % concentration	Polypropylene with 30 % mineral filler	›PP-MD30‹
Thermoplastic with "more than one" Additive used at > 1 % concentration	Nylon 66 with 15 % mineral filler and 25 % glass fiber reinforcement	›PA66-(GF25 + MD15)‹ or ›PA66-(GF + MD) 40‹
"Multi-material" thermoplastic product	A PVC coated polyurethane containing an ABS insert that is the major component by mass	›PVC, PUR, ABS‹

* Product marking to be molded in, embossed, melt imprinted or by other legible and indelible process.

the appearance of the thermoplastic item, if marked externally. There can be added manufacturing concerns associated with creating the mark. There can also be concerns associated with ink contamination for the recycled items in the case of printed markings (rather than molded-in markings). However, marking can normally be implemented successfully without any significant negative impact. It is also important to note that if there is ever a change in material during the production run of an item, the product material marking code should be immediately altered to reflect the material change as well. As material code marking practices and sorting technologies evolve, recycling rates for parts that have been properly marked are likely to increase, because proper material identification and subsequent segregation are critical components to most thermoplastic recycling operations. Examples of ASTM material codes for filled and multi-material products are given in Table 7.2.

7.2.3 Minimize Components and Materials of Construction

The thermoplastic products that are most easily recycled are those that are entirely produced from one single grade of thermoplastic. This is easily achieved with single component items such as the disposable (but recyclable) thermoplastic cutlery used in a cafeteria, as an example. Thermoplastic forks, spoons, and knives are all single component, single material products. Even though each of these items has its own specific (but very similar) end use requirements, it is likely that each could be produced from exactly the same grade of thermoplastic (i. e., the same thermoplastic and additives) to eliminate the need for any material segregation prior to washing and recycling. Taking this a step further, it would be ideal from a recycling standpoint, if all of a cafeteria's disposable (but recyclable) thermoplastic food service items, such as the cutlery, cups, plates, etc. could all be produced from exactly the same grade of thermoplastic. This use of the single, common thermoplastic "material of construction" would result in greater quantities of material for recovery and it eliminates the need for individual item identification and sortation, greatly simplifying the recycling process, and thereby reducing the overall cost of recycling.

Unfortunately, most consumer or industrial products have more complex geometric and functional requirements than the disposable food service items described above. The majority of these products have end use requirements or geometries that necessitate a multi-piece and often multi-material construction. Minimizing the number of individual parts and materials that make up a product are primary teachings of the *Design for Manufacturability* philosophy. However, it is rarely possible to achieve the ultimate goal of a single material, single component product construction, unless the product geometry and functional requirements are relatively simple. Single component product construction is possible in some applications because thermoplastics can be molded into items with very complex geometries. For example, it is often possible to achieve single material, single component construction using creative design concepts such as the integral "living" hinge that is commonly used for clamshell and other types of thermoplastic items. The living hinge concept is most widely used with tough semi-crystalline materials such as polypropylene.

In some cases, single material, single component construction is not possible for reasons that are related to the limitations of the specific manufacturing process used to make the product.

Figure 7.4 The polypropylene video game case can be molded as one piece by incorporating a number integral or living hinges making this a very recyclable part design

In yet other cases, single component construction is not possible for reasons related to the end use or functional requirements of the product. A variety of different thermoplastics or other materials may be required for the application. If at all possible, it is best from a recycling standpoint, if the different components that make up the multi-component product can all be manufactured from one single grade of material. In cases where the multi-component product construction is required only for manufacturability reasons, it is usually possible and typically easier to produce the individual parts that make up the product from the same grade of material.

In other cases, where some of the individual product components have very different functional requirements, it may not be possible to find one single thermoplastic material with all of the necessary properties or attributes. If more than one material type must be used, the number of materials utilized should be minimized by making as many components as possible from common material grades. The materials that are used for multi-component/multi-material products must first be functional, but should also have characteristics that simplify or facilitate recycling whenever possible. A number of design options that enhance the recyclability of multi-component/multi-material products are discussed in the following sections.

7.2.4 Multi-Component Product Recycling: Design for Disassembly (Pre-Granulation)

The products that are most easily recycled are those that are manufactured all as one piece from a single material. However, most products have either geometric or functional requirements that call for a more complex construction and a number of component parts. For example, the product may contain a number of components manufactured from a variety of different thermoplastic and non-thermoplastic materials. The various component parts that make up the product are attached in some way to produce the functional product assembly. Each individual component in the assembly has its own specific function and material property requirements. Those components with similar or equivalent requirements are usually produced from the same material to minimize the number of materials used in manufacturing. The recycling of multi-material, multi-component products can be a challenge, both technically and economically.

When the materials that make up the individual component parts of a product are different, it is generally best, from a recycled material quality viewpoint, if each material type is recycled as an individual material stream. The "material separation" step required to implement individual material stream recycling can add very significant cost to the recycling process, especially if the product has not been designed to facilitate separation. There are two fundamental ways in which this separation can be accomplished. One approach is "bulk granulation" of the non-separated product (or of a product that has undergone limited separation). The entire product is granulated and material segregation is achieved "post granulation" using physical property differences, such as differences in density, magnetism (for ferrous metal separation), thermal or electrostatic characteristics. The second approach to individual material stream recycling for multi-component, multi-material products is component (hence material) segregation "prior to granulation". This second approach to multi-component product recycling is also known as "demanufacturing" or "dismantling". Both recycling approaches have their own relative advantages and limitations. The pre-granulation or disassembly approach to multi-component product recycling is discussed later in this section, and is most appropriate for products that have been specifically designed to simplify disassembly.

Demanufacturing is becoming a relatively common approach to recycling for durable goods, such as automobiles, appliances, computers, and other business machines. The plastic, glass or metal components that are recovered from durables demanufacturing operations are sometimes reused or "rebuilt", but are more commonly mechanically reground for secondary recycling. Non-hazardous recovered components that are not readily recyclable are normally landfilled or incinerated. Recycling decisions regarding which specific material streams to be recovered or "cherry picked" from the product, which components will be segregated or commingled (e.g., for similar thermoplastic grades), the level of cleaning, etc. are made by the recycler on a case by case basis. It is also common to shred or granulate the recovered (segregated) streams at or near the dismantling site to save on transportation costs for bulky or lightweight items.

If we make the assumption that the infrastructure for such a demanufacturing operation does exist, there are a number of *Design for Enhanced Recyclability* issues that become important. Most of these issues are addressed in other sections of this chapter. For example, it is important