2 Shrinkage and Warpage

Mold shrinkage (in-mold shrinkage or *molded-part shrinkage* are more accurate terms), although a volume phenomenon, usually refers to the difference between the linear dimension of the mold at room temperature and that of the molded part at room temperature within forty-eight hours following ejection.

Warpage, a distortion of the shape of the final injection-molded item, is caused by differential shrinkage; that is, if one area or direction of the article undergoes a different degree of shrinkage than another area or direction, the part will warp.

Post-mold shrinkage is another common shrinkage term. It refers to any additional shrinkage that occurs after the initial 48-hour period.

Shrinkage and warpage tendencies in molded parts are influenced by actions taken in each and all of the manufacturing stages of part design, material selection, tool design, and processing. Subsequent chapters examine particular causes of shrinkage and warpage arising in each of these stages. This chapter presents an overview of shrinkage and warpage phenomena, with emphasis given to identifying conditions where shrinkage and warpage behave in a regular manner, allowing for prediction and corrective action.

2.1 In-Mold Shrinkage

In-mold shrinkage tends to respond to changes in molding conditions as shown below.

An increase in:	Effect on shrinkage:
Injection pressure	Decreases (usually)
Injection rate	May be either (minor effect)
Holding pressure	Decreases
Holding-pressure time	Decreases until gate freeze
Melt temperature	May be either
Mold temperature	Increases
Clamping pressure	Usually none; may decrease
Wall thickness	May be either; usually increases
Melt flow rate	Decreases
Ejection temperature	Increases
Cooling time	Decreases
Gate minimum dimension	Decreases
Number of gates	Decreases
Amount of filler	Decreases
Kind of filler	May be either
Mold-open time (operator break)	May be either

Environmental factors may have subtle effects on actual mold or melt temperature:

An increase in:	Effect on shrinkage:
Room temperature	Increases
Humidity	Increases
Air movement	May be either; usually decreases

Note a prevalence of processing factors in the above list. Other predictable molding process conditions that affect shrinkage can be observed on the shop floor. In particular, use of a molding machine that is too small may contribute to shrinkage variation through inadequate clamping pressure or plasticizing capacity. A machine which is too large can cause excessive heat history and resultant degradation of the material. There is also an unfortunate tendency of setup workers to use the maximum available clamping tonnage, even on small molds. Platens are sometimes bent because high clamping tonnage is applied to a mold that is very small compared to the size of the platens. Molds can be damaged by this practice. Variations in the molding cycle affect the shrinkage. When the molding machine gate is left open for any reason (while the operator goes to the lavatory) the next plastic injected into the mold is hotter and the mold temperature is usually cooler than the previous shot.

In general, during processing, at the instant a mold cavity fills, the pressure differential from the gate to the furthest extremities is at its lowest level. As the material cools, it typically solidifies first at the farthest point from the gate. This allows the pressure nearer the gate to be maintained at a higher level until the gate freezes. This final differential pressure can be significantly greater than the differential pressure right after the cavity fills. Gating into the thickest part of the molding tends to minimize the effects of this differential pressure.

The way in which the mold is filled influences the direction, degree, and type of molecular orientation in the molding, especially near the surface. As the material flows into the mold, a spherical volume of material in the melt front is stretched as it advances into an ellipsoidal shape, as shown in Fig. 2.1.[2] The ellipsoid formed can be many times greater in length than in width resulting in almost total straightening of molecular strands and reinforcing fibers in the flow direction. Dramatic evidence of this shape change can be found in foamed injection-molded parts. The silvery streaking on the surface is actually a multitude of formerly spherical bubbles that have elongated (stretched) as they approach the wall of the mold. An inspection of this type of part indicates that any single streak is many times longer than it is wide.

The flowing, stretched plastic is cooled rapidly by contact with or proximity to the mold wall; the fiber and molecular orientations are retained. While this is happening, fresh material flows between the frozen surface layers to create a new melt front. This process continues until the mold is full. Relaxation and randomization take place rapidly in the melt if it has a low viscosity, and orientation is therefore highest when the melt temperature is relatively low. On the other hand, high melt and mold temperatures give more time for randomization and can reduce the tendency to warp. A compromise may be necessary between product quality and production economics because low melt temperatures reduce cycle times.

2.1.1 Determination of Shrinkage

ASTM D955-00 is the American document (related document: European Standard ISO 294-4) that specifies the standards that are to be used to determine shrinkage of plastics.[5] It states that the difference in size of the molded part and the mold is "shrink" and is affected by a variety of factors. Among the factors causing variation in the actual shrinkage are:

- The size and shape of the part
- The size and length of the runners, gates and machine nozzle
- The wall thickness of the part
- How the mold works and the effectiveness of the cooling channels in the mold
- The flow patterns within the mold
- The molding machine settings including holding times and pressures

Minimum shrink will occur when a maximum amount of material is forced into the mold cavity for the longest possible time as a result of adequately sized flow channels, and when pressure is maintained at an adequately high level until the plastic is thoroughly hardened. High shrinkage will occur when an inadequate amount of plastic is forced into the mold and the pressure on the plastic is maintained for too short an interval of time. High viscosity materials make it more difficult to maintain adequate mold pressure, therefore tend to shrink more.

The plastic whose shrinkage is to be determined may require some special preparation before it is molded. For example, some thermoplastics absorb moisture, even from the air, and must be dried before they are introduced into a molding machine. The sample should be prepared according to the material manufacturer's recommendations, and a record of those preparations should be included as part of the shrinkage report.

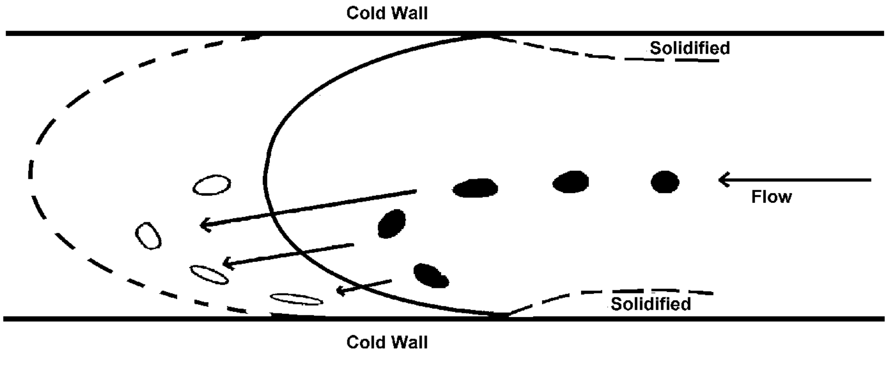

Figure 2.1 The diagram shows how a spherical volume of plastic changes shape as it flows into a mold. This is one of the mechanisms that cause fiber and molecular orientation.[2] *(Reproduced by permission of Oxford Science.)*

The cavity size for measuring shrink parallel to the flow of the material will normally be 12.7 by 127 mm (1/2 × 5 in.) with a thickness of 3.2 mm (1/8 in.). The gate will be at one end and normally be 6.4 mm (1/4 in.) in width by 3.2 mm (1/8 in.) in depth. If the test mold and gate vary from the above for any reason, the variance must be included in the test report. When shrinkage in both directions, parallel to and perpendicular to the flow, are to be determined, the mold will normally have a cavity 102 mm (4 in.) in diameter by 3.2 mm (1/8 in.) in thickness, edge-gated 12.7 mm (1/2 in.) in width by 3.2 mm (1/8 in.) in depth.

These molds produce test specimens that can be measured to determine the appropriate shrink. For shrinkage parallel to the flow, the long bar will be used and its length measured and compared to the mold. For diametral shrinkage, across and along the flow, the disk produced by the mold will be measured and compared to the mold both from the gate to the opposite side and in a direction perpendicular to the first measurement.

The proper procedure to determine the shrink of the plastic sample is to mold at least five good parts under proper molding conditions as agreed upon by the plastic supplier and end user. In the absence of recommended or agreed molding conditions, ASTM D955-00 recommends a procedure to achieve good molding conditions. ASTM Practice D1897 should be used as a guide for molding conditions. The molding machine should be of such a size that the sample parts being molded use about one-half to three-quarters of the capacity of the injection unit. (Too large a machine will develop excessive heat history and too small a machine will not produce consistent results.) After the samples are molded, the length of the bar cavity or the diameter of the disk cavity is measured to the nearest 0.001 in. (0.02 mm).

The shrink factor is determined by measuring the test cavity and the piece molded therein, subtracting the length of the part from the length of the cavity, and dividing that result by the length of the cavity. The measurements should be made as soon as the sample part has cooled to laboratory temperature and again after forty-eight hours. Measurements of five (or more) samples should be averaged. The shrinkage should be expressed in inches per inch of length or millimeters per millimeter of length (the values should be identical). Any material preparations made before molding and all molding conditions should be included in the report.

2.1.2 Molded-in Stress

Changes in molding conditions that reduce shrinkage usually increase molded-in stress. Mechanical properties depend directly upon the relationship between the axis of orientation of the plastic molecules and the axis of mechanical stress upon these molecules. Reversible properties, such as modulus and stiffness, increase in the direction of orientation because stress along the axis of the molecules is applied against the strong covalent bonds within the molecules, whereas perpendicular stress is applied only against the weak secondary forces between the molecules. Therefore, in the direction perpendicular to the axis of orientation, modulus decreases and flexibility increases. These effects are important to the toughness and flexibility of most films and all fibers.

Ultimate tensile strength generally increases in the direction of flow or stretch and decreases in the perpendicular direction. Changes in strength also relate to possible existing stress concentrations (such as microscopic or submicroscopic flaws) that may develop parallel to the axis of orientation. When stress is applied perpendicularly to the axis of orientation, it tends to pull the flaws open, but when stress is applied along the orientation axis, it does not. Moderate orientation, particularly in rigid amorphous plastics like polystyrene (PS), increases ductility and ultimate elongation in the orientation direction and decreases them in the transverse direction. High degrees of orientation of ductile plastics can have the opposite effect by using up most of a plastic’s inherent extensibility.

Biaxial orientation (BO) increases impact strength significantly, making BO very desirable in most packaging films. With monoaxial (uniaxial) orientation, impact strength increases in the direction of stretch; the material’s ability to withstand transverse impact is very weak and it usually breaks into bundles of fibers when the impact strength is tested. These impact results can be related to the area under the tensile stress-strain curves; the BO film has a much larger area under the curve that can be used as a measure of toughness.

The mechanical properties of reinforced plastic (RP) are even more affected by fiber orientation. A major advantage of using RPs is the design engineer’s ability to maximize directional properties; they can be isotropic, orthotropic, anisotropic, etc. Basic design theories of combining actions of plastic and reinforcements have been developed and used successfully since the 1940s, based originally on work with wood-fiber structures.

As an example, woven fabrics that are generally bidirectional at 0° and 90° angles contribute to the mechanical strength at those angles. The rotation of alternate layers of fabric to a lay-up of 0°, +45°, 90°, and -45° alignments reduces maximum properties in the primary directions, but increases them in the +45° and -45° directions. Different fabric patterns are used to develop different property performances.

Injection molding of RPs causes some inherent orientation of the reinforcing fibers. The orientation increases the difference in strength and shrinkage between the flow and transverse directions. As melted, the molecules of a polymer are randomly oriented and intermixed so that strands of one molecule cross and intermix with the strands of many other molecules. As the material flows under the influence of the injection molding machine, the high viscosity of the polymer causes laminar flow to develop and, as a result, tends to disentangle the molecules and orient them in the direction of flow. The greatest amount of this type of orientation takes place in restricted areas such as gates where very high shear rates are found. As the material spreads into the mold from the gate, some additional reorientation takes place. Turbulence and Brownian randomization can reduce this orientation somewhat, although some of the extreme orientation triggered by the gate will be retained in the direction of flow.

When the material contains short glass fibers or other reinforcements, their orientation will also be determined by the flow pattern. Figure 2.2 shows a section through an injection-molded part made from glass-reinforced polypropylene. Near the surface, the fibers are oriented predominantly in the flow direction, while in the central region they are randomly oriented.[2]

2.2 Warpage

Warpage causes a part to bend or twist out of shape and alters not only the dimensions but also the contours and angles of the part. This is more readily noticed in large- and flat-molded articles and, though undesirable in any molding, is particularly objectionable in such items as container covers, closures, or drain boards. Warpage is related to the phenomenon of material shrinkage. It results when differential or nonuniform shrinkage occurs within a part.

Some nonuniform shrinkage results from poor part or tool design. Part wall-thickness and geometry are major design factors. Some causes of warpage are dissimilar wall sections, gating in a thin section of a part, placing the sprue incorrectly (especially in sprue-gated parts), or cores that cause weld lines. Computer-aided process simulation software packages can be used by the part designer to optimize the part and tool designs, and minimize the potential for shrinkage and warpage long before the mold is built or the part is processed. Such software tools are examined in Ch. 9. However, it cannot be overemphasized that an experienced mold designer and builder will recognize potential hazards

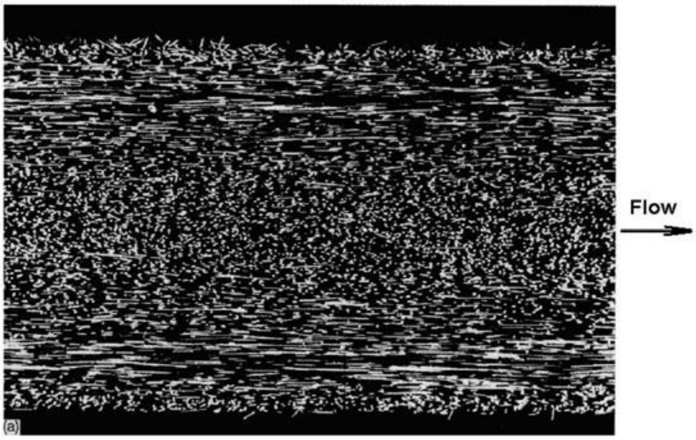

Figure 2.2 Section parallel to the flow direction through a glass-reinforced polypropylene injection molding shows that the short fibers near the surface are oriented parallel to the flow direction while those in the central region tend to be transverse to flow.[2] *(Reprinted by permission of Oxford Science.)*

in a part or mold design and do everything possible to avoid molding problems. Computer-aided process simulation results can be worse than those of guesses made by experienced mold builders. An inexperienced software user can use the simulation program inappropriately and produce misleading results. In other words, it is a mistake to rely on computer-aided process simulations unless the operator is very experienced and has good references. The human factor is a major phenomenological element influencing part shrinkage and tool design.

Some nonuniform shrinkage is a result of the choice of material. Some plastics, particularly the semicrystalline ones , have anisotropic shrinkage characteristics. Amorphous thermoplastics are less prone to warpage than crystalline resins. Semicrystalline materials naturally shrink more than amorphous materials because the crystals formed during cooling take up less volume than the unoriented (amorphous) molecules that exist during the melted phase. While high shrinkage alone does not cause warpage, it increases the probability that warpage will occur. All plastic molecules tend to orient in the direction of flow, but the orientation of semicrystalline materials leads to anisotropic shrinking. When the molecules are oriented in the direction of flow, they tend to stack into the crystal form with the molecular fibers parallel to the direction of flow. There is little change in length along the fibers, but the fibers nestle together and shrink more across the direction of flow. This usually results in greater shrinkage across the flow direction. However there is a greater tendency in some materials, especially acetal and nylon 66, for the fibers to fold back on themselves as they crystallize, which increases the shrink in the flow direction. Flow/cross-flow shrinkage differences tend to become more significant as the average molecular weight of the polymer increases.

Some nonuniform in-mold shrinkage is due to packing-rate differences and other processing factors. If a part has molded-in stresses, the stresses force the part to try to assume its natural or relaxed state. One challenge for the molder, and it is often a significant problem, is to mold the part in such a manner that the molded-in stresses are minimized. The common causes of molded-in stresses are uneven cooling, a melt temperature that is too low, and excessive injection pressure. Orientation is increased with increasing fill rates, decreasing mold or melt temperature, decreasing wall sections, and converging (as opposed to diverging) flow. Diverging flow can be represented by a disk gated in the center. Converging flow would occur in a tapered rod or wedge shape that is gated on the large end.

Nonuniform mold shrinkage behavior is an undesirable phenomenon in injection molding since it can lead to the following:

- Distortions of the finished part (warpage)
- Difficulties in hitting the target dimensions
- Higher internal stress levels

2.2.1 Common Causes of Nonuniform Shrinkage

Shrinkage differentials may be due to any of the following conditions.

Differential Orientation. In general, oriented material with molecules or fibers aligned or parallel shrinks in a more anisotropic manner than unoriented material. The degree of orientation imparted to the melt during the mold filling process has a large influence on the shrinkage exhibited by the plastic material. During mold filling, the polymer molecules undergo a stretching that results in molecular orientation and anisotropic shrinkage behavior. Natural, unfilled plastic materials tend to shrink more along the direction of flow (in-flow shrinkage) compared to the direction perpendicular to flow (cross-flow shrinkage), while the shrinkage behavior of reinforced materials is restricted along the direction of fiber orientation. In general, mold shrinkage will tend to be more isotropic when the degree of orientation imparted to the melt during mold filling is minimized, and when favorable conditions for molecular relaxation exist.

Differential Crystallinity. For semicrystalline materials, if some part of the mold cools at a slower rate, that area will have higher crystalline content and, hence, higher shrinkage. This is the case for parts with different thicknesses, and for hot spots such as where material is in contact with outside corners of a core or with core pins.

Differential Cooling. This can occur when the mold surfaces are at different temperatures, as they frequently are around core pins, inside and outside mold corners, near gates, and where there are section thickness variations. Hot spots cause problems in two ways: with added crystallinity, and with a longer/later cooling time. (The last area to cool acts as if it were shrinking more.)

Material Characteristics. Copolymers are better than homopolymers at resisting warpage. Certain types of fillers reduce overall shrinkage and increase stiffness.

Differential Thermal Strain. This may be due to geometric effects, that is, where there are section thickness changes, sharp inside corners, or other geometric conditions that cause variable cooling or unusual orientation. The more abrupt the change, or the greater the differential cooling rate, the more severe the thermal strain.

Molding Conditions. These can lead to excessive stresses caused by unusually high or low melt temperature or pressure, or unusually long injection time or short cycles.

Mold Constraints. Mold constraints can contribute to nonuniform shrinkage. Usually the part is free to shrink in thickness. It is usually less free to shrink in length and width due to the geometry of the part. There may be cores, ribs, or edges that are firmly anchored so that the part cannot move until it is out of the mold.

2.2.2 Principles of Minimizing Warpage

The difficulty in trying to minimize warping is that the conditions necessary to do so are sometimes the opposite of those conditions needed to obtain minimal shrinkage. For example, highly cooled molds cause lower average linear shrinkage but encourage warpage, especially in pieces with high surface/thickness ratios.

Often the methods used to minimize molded-in stress result in unacceptably high shrink rates. The best resistance to warpage calls for warm molds, high material temperatures, low injection pressures, and short injection/hold times. Minimum shrinkage outside of the mold requires just the opposite. Therefore the molder is usually faced with difficult compromises to minimize both warpage and shrinkage. Warm molds and high melt temperatures allow more time for the molded part to “relax” before it solidifies. Low injection pressures minimize the stress caused by high-velocity flow through the gate. Short injection and hold times minimize packing stress.

Unreinforced materials especially require uniform wall sections. Sections that vary in thickness result in nonuniform flow and cooling. Multiple gates can help maintain uniform cavity pressure which leads to more uniform shrinkage. As always, the temperature control system must maintain a uniform cooling rate throughout the part.

When molding with fiber-reinforced materials, the symmetry of the molded part is of supreme importance. If the part is not symmetrical, then the flow through the mold also will not be symmetrical. Consequently, the fiber orientation will be irregular which leads to uneven shrink and resulting warpage. Each weld line is a potential cause of warping. Therefore, the placement of cores and gates is important. If there are cores on one side of a molded part that cause weld lines, it may be necessary to place blind cores on the opposite side of the part to balance the warp tendency caused by the required cores and weld lines.

Cooling-related shrinkage differences exist for all polymers, but are a particular concern for semicrystalline polymers. As the name implies, semicrystalline polymers are only partially crystalline, with the remainder of the matrix being amorphous. The ability of a semicrystalline polymer to pack neatly into a crystalline lattice is improved when the polymer is cooled more slowly. The mold shrinkage that a semicrystalline polymer exhibits will therefore be influenced by the rate of cooling due to its effect on percent crystallinity (see also Sec. 6.3). This cooling-rate/percent-crystallinity relationship also accounts for variations in the crystalline morphology of the material through the thickness of an injection molded part.

The shrinkage behavior of a semicrystalline polymer is therefore far more complicated than that of an amorphous polymer. The effect of part thickness on mold shrinkage is very significant with semicrystalline polymers. The general type of behavior that can be expected is shown in Fig. 2.3.

Higher mold shrinkage values can be expected for semicrystalline polymers when thicker wall sections are used due to the increase in cooling time (and time for crystallization to occur) associated with the thicker wall.

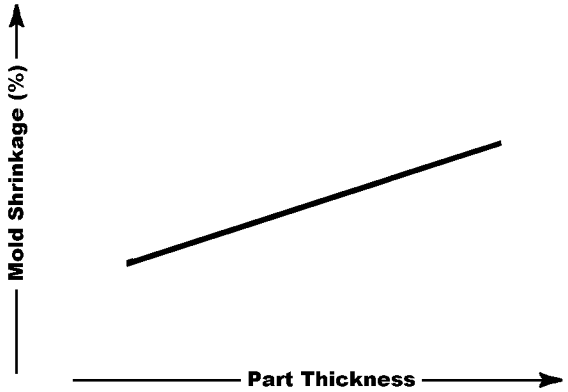

Figure 2.3. Relationship of part thickness to shrinkage for semicrystalline polymers.

This can be a particular concern when molding parts with variable wall thicknesses. For example, in applications where reinforcing ribs are used to stiffen flat parts, the ribs are typically thinner than the nominal wall thickness from which they extend. This practice limits the size of the sink opposite the rib that is a result of the unavoidably thicker section at the juncture. However, the slower cooling rate for the nominal wall and juncture (thicker sections) will lead to an increase in shrinkage, and the potential for concave warpage in a direction away from the ribs. Crystal orientation and shear-induced crystallization also complicate the shrinkage behavior of semicrystalline polymer.

For example, suppose the outer 1 mm of a 5-mm thick part tends to shrink by 1% because the outer layer cools faster, under higher pressure, with less crystallization than the center of the part. Cooling and shrinkage after the gate freezes causes the center of the part to experience a lower pressure than the walls, which solidify while the gate is still open and maximum injection pressure exists. The center of the part, cooling slower and under lower pressure with a resulting greater percentage of crystallization, tries to shrink by 2%. In this case, the actual measured shrink would be

$$\frac{2}{5}+2\left(\frac{3}{5}\right)=1.6\%$$

The outer skin compresses slightly as the core stretches slightly.

In practice, there is no sharp dividing line between one shrink rate and another. Rather there is a gradual change in the “natural” shrink rate from the surface of the part to the core, and the average shrink for the total thickness is the result of each infinitesimal layer affecting the layers on either side of it.

Taking this example a step further, if one side of the mold is cooler than the other side, then the layers on the cooler side will be thicker than the layers on the warmer side, and will resist shrink more than the thinner layers. The end result will be that the part will tend to shrink more on the warmer side. If the part is flat, this will cause the part to warp with a concave curve on the warmer side.

Even when the mold cavity walls are uniform in temperature, asymmetry can cause differential cooling problems. Consider Fig. 2.4. Any variation in wall thickness will cause differential cooling rates and a tendency for the part to warp so that the heaviest wall will be somewhat concave.

When a part warps after being ejected from the mold, it assumes its “natural” form by relieving the unnatural stresses forced upon it while being shaped in the mold in a viscous state. The problem for the molder—and it is often a difficult one—is to minimize the “locked-in” stresses which the item might later “remember,” and relieve them when cooling to room temperature or on later exposure to higher than normal heat. The locked-in stresses are generated in the mold by such operating conditions as excessive molding pressures, uneven cooling, or a melt temperature that is too low, to mention only a few causes.

Usually, a number of plastics can be used to satisfy a particular purpose. Many of the semicrystalline materials have good lubricity; however, their greater shrink rate and tendency toward warpage may suggest that the designer consider using a lower shrink, amorphous material with a lubricant filler. This is especially important if tight tolerances are a requirement. In some cases, a change in material may be possible to minimize shrinkage or warpage problems provided that the material change does not cause the size of the molded part to be out of tolerance as a result of the change in shrinkage. Glass-filled polypropylene is increasingly used to fill requirements formerly filled with so-called “engineering” grades of plastic. This can be an attractive option if the higher shrink rate of the polypropylene (especially across the direction of flow) does not cause unacceptable warpage or size problems.

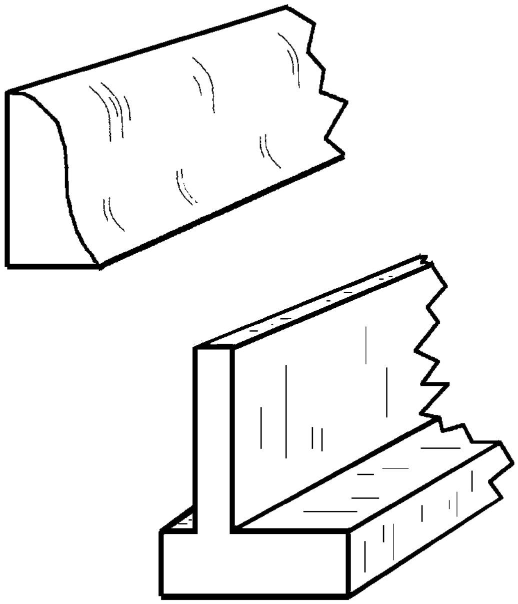

Figure 2.4 In asymmetric parts like these, there will be a cooling rate differential between thick and thin areas.

2.3 Post-Mold Shrinkage

Cold molds and rapid cycles tend to freeze stresses in a molded part while reducing its apparent shrinkage. Later, with exposure to time and/or temperature and moisture, additional shrinkage can occur. Shrinkage that occurs more than forty-eight hours after molding is considered to be post-mold shrinkage. In higher shrink materials such as acetal and nylon, the post-mold shrinkage can be significant. While higher mold temperatures require longer cycles, cost more, and produce parts with more apparent shrinkage, the total shrinkage and post-mold shrinkage are less.

Parts molded in the injection molding process are molded dry. They initially contain virtually no water. Some materials, especially nylon, absorb moisture from the environment. Nylon needs water to develop its best physical characteristics. Dry, it is brittle. Moisture absorption and size change for several resins are shown in the appendix entitled “Data,” of this book (and in reference books such as *Modern Plastics Encyclopedia*[59] and in literature available from plastics suppliers).

Nylon is an excellent material, but consideration should be given to any size change when hygroscopic materials are exposed to moisture in product-service use. Hygroscopic materials have an affinity for water to such an extent that they will absorb a significant percentage of their weight in water. Nylon and the cellulosics are most vulnerable to size change due to moisture. If only one side of a hygroscopic material is exposed to water, that one side may grow in length to such an extent that the part warps (bows convex toward the moisture) to a significant degree on the wet side. Various plastics often absorb water or other liquids to a degree that makes the plastic unsuitable for a particular application. Even though the moisture absorption of polycarbonate is quite small compared to nylon, CD discs, which are metallized on only one side, can bow beyond their tight tolerances. The chemical resistance of a plastic needs to be matched to whatever environmental fluid it is likely to encounter. If the supplier states that a plastic is compatible or resistant to a fluid, that usually means that it absorbs less than 1% of the fluid. On the other hand, some plastics contain fluids such as plasticizers that tend to migrate or “boil off” with time. The loss of fluids usually causes shrinkage and increased brittleness.

Chapter 7 of this volume contains additional information and a discussion in greater depth of the absorption of various liquids. The effect of elevated temperature and its tendency to encourage annealing of thermoplastic parts and how that affects size change is presented there. And finally, plastics creep. This means that if a significant load is placed on a plastic part, it will move or sag. The longer the load is applied, the more the plastic part will deflect. This characteristic of plastics is often overlooked and has been a major cause of component failure. More often than not, when a plastic part fails, creep is directly or indirectly involved in the failure, and the failure is a result of bad design. Unfortunately, the plastic gets the blame and not the deficient design.