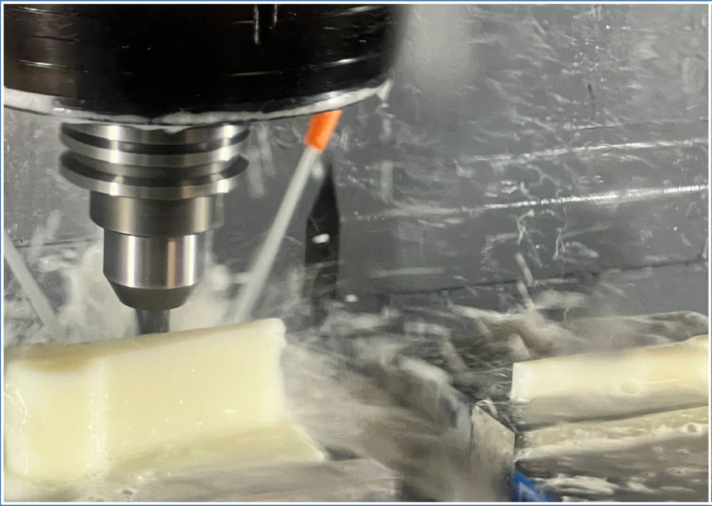
DIMENSIONAL TOLERANCE CHALLENGES WITH PLASTIC PARTS



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CURBELL PLASTICS

Table of Contents

Drawings of plastic parts often specify tolerances that are tighter than the practical limitations for the polymers.

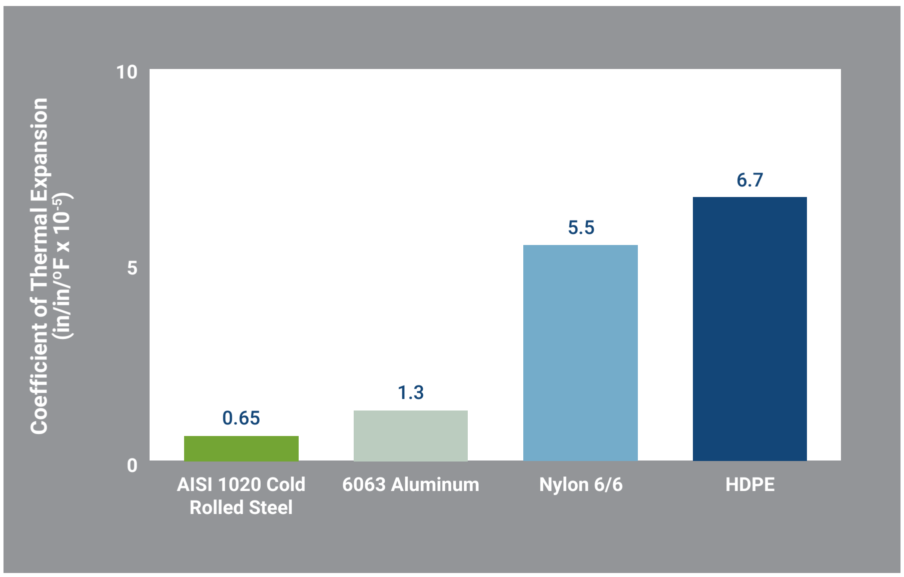
BACKGROUND / SCOPE

Plastics are less dimensionally stable than metals, ceramics, or wood products. For this reason, plastic parts require more open dimensional tolerances compared with the tighter tolerances that can be achieved with these other types of materials. Drawings of plastic parts often specify tolerances that are tighter than the practical limitations for polymers. This creates frustration for both fabricators who are unable to achieve the specified tolerances and designers who struggle to source the parts as drawn. The purpose of this paper is to explore the factors that contribute to dimensional changes in plastics so that readers will have a richer understanding of this topic.

THERMAL EXPANSION

Coefficient of thermal expansion (CTE) describes the rate at which a given material will expand when heated or contract when cooled. One of the major causes of dimensional changes in plastic materials is their relatively high CTE values compared with those of metals. Figure 1 below shows the thermal expansion rates for AISI 1020 cold rolled steel, 6063 aluminum, nylon 6/6, and high density polyethylene (HDPE).

Figure 1. Coefficients of Thermal Expansion for Various Metals and Plastics



The higher thermal expansion rates of plastics compared with metals can create challenges for designers. For example, the tool chest shown below consists of a base cabinet made from cold rolled steel and a top made from high density polyethylene (HDPE). The recessed opening at the top of the steel cabinet is 30" wide at room temperature (72ºF). The designer specified the HDPE top to be 29.97" wide at room temperature, allowing 0.030" of clearance for easy assembly of the top to the cabinet. However, when the tool chest was placed outside on a summer day, its temperature increased from 72ºF to 100ºF.

This HDPE tool chest top warped when placed outside on a warm day due to its high rate of thermal expansion.

Due to the different thermal expansion rates of the two materials, at 100°F the HDPE top expanded beyond the dimensions of the recessed opening in the steel cabinet per the calculations shown in Table 1.

Table 1. Thermal Expansion Calculations for the Initial Tool Chest Design

	Dimension at 72°F (inches)	Temperature Change (°F)	Coefficient of Thermal Expansion (inch/inch/°F x 10^{-5})	Dimension at 100°F (inches)
Recessed Opening in Steel Cabinet	30.00	28	0.65	30.005
HDPE Top	29.97	28	6.70	30.026

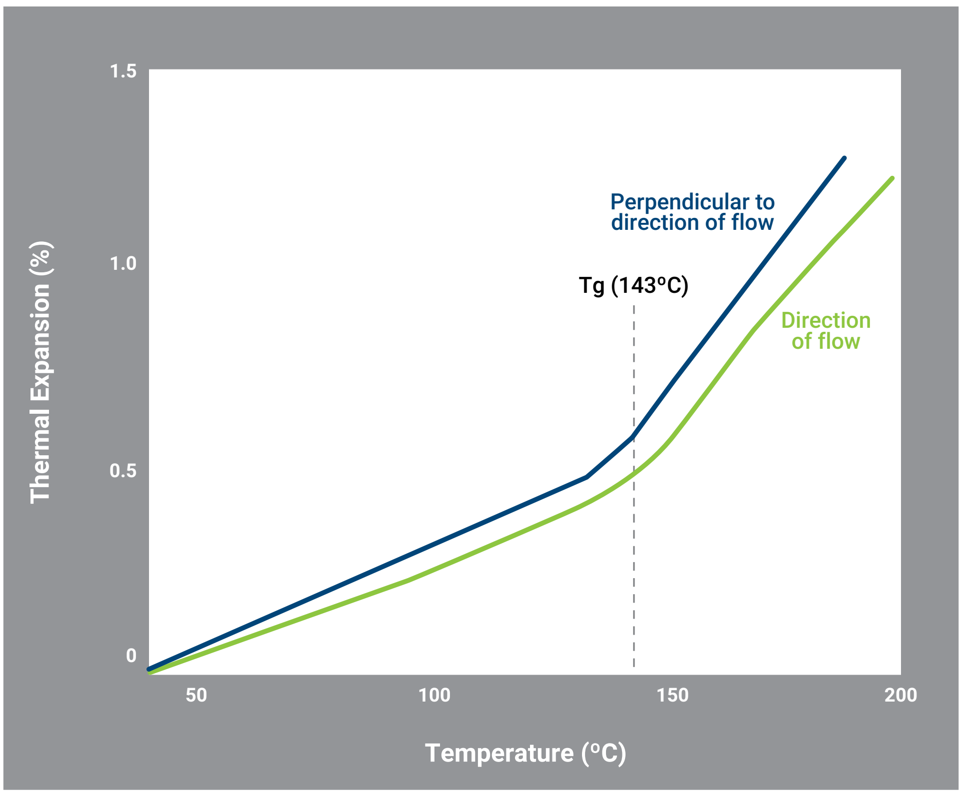
This resulted in the top warping due to thermal expansion mismatch. The design was revised to have 0.060" of clearance between the HDPE top and the recessed opening of the cabinet to give the top sufficient room to expand at elevated temperatures. Thermal expansion calculations for the revised design are shown in Table 2.

Table 2. Thermal Expansion Calculations for the Revised Tool Chest Design

	Dimension at 72°F (inches)	Temperature Change (°F)	Coefficient of Thermal Expansion (inch/inch/°F x 10^{-5})	Dimension at 100°F (inches)
Recessed Opening in Steel Cabinet	30.00	28	0.65	30.005
Revised HDPE Top	29.94	28	6.70	29.996

Although the plastics industry frequently reports a single value for the CTE of a given material, there is often a more complex relationship between temperature and part dimensions. For example, Figure 2 shows that the coefficient of thermal expansion of polyetheretherketone (PEEK) more than doubles above the material's glass transition temperature (Tg) of 143ºC. Additionally, PEEK has a lower CTE in the direction that the resin flowed during molding compared with its CTE in the transverse direction.

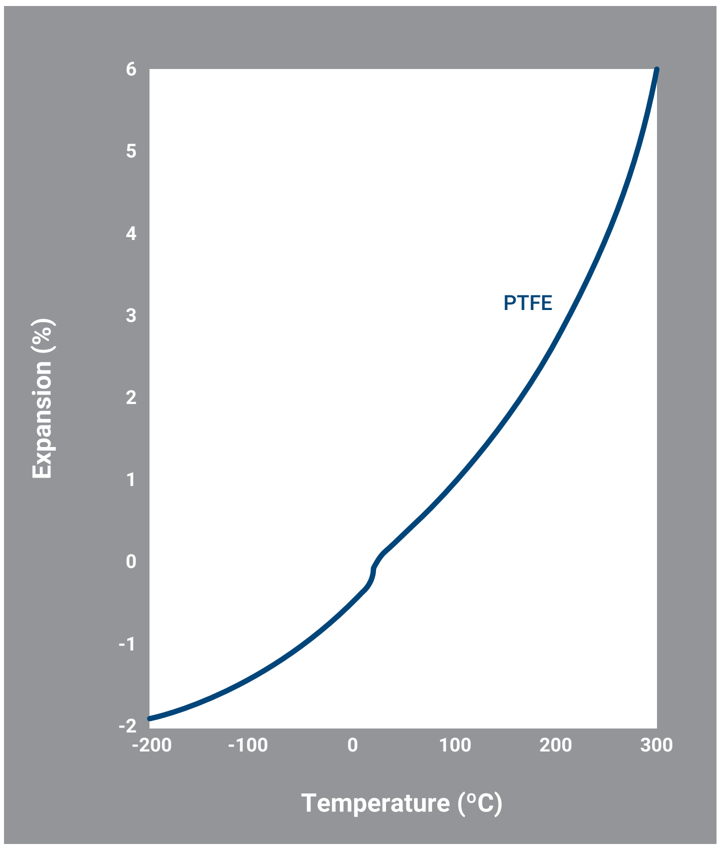
Figure 2. Thermal Expansion Curves for PEEK in the Direction of Flow and Perpendicular to the Direction of Flow, Both Above and Below the Material's Glass Transition Temperature



Source: Adapted from Jiang, 2021

Some plastic materials exhibit even more complex thermal expansion behavior. Figure 3 shows the thermal expansion of PTFE from -200ºC to 300ºC. The rate of thermal expansion for this material changes at 20ºC and 30ºC. This complicates the design of assemblies that include metal and PTFE mating components that experience a wide operating temperature range since the PTFE components will grow at a much faster rate than the mating metal parts when the device is heated.

Figure 3. Thermal Expansion of PTFE from -200°C to 300°C



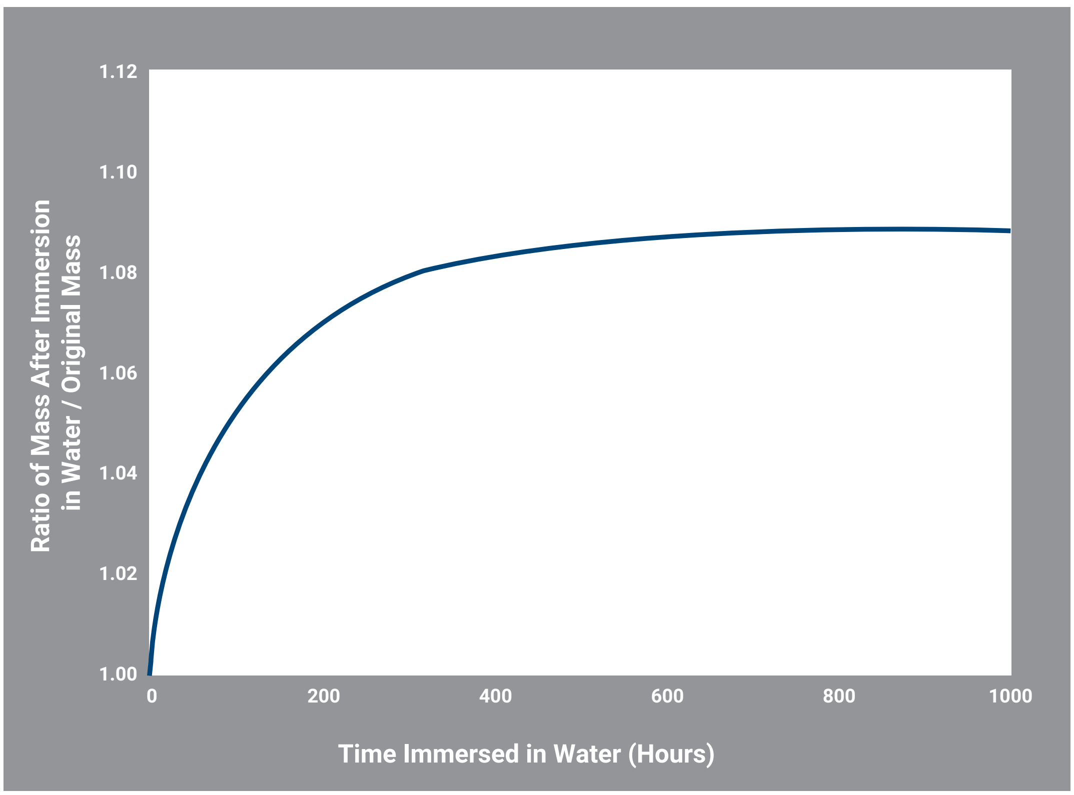
Source: Adapted from Kirby, 1956

Fillers such as glass fibers or carbon fibers can be used to reduce the CTE of thermoplastics for applications where improved dimensional stability is required.

WATER ABSORPTION

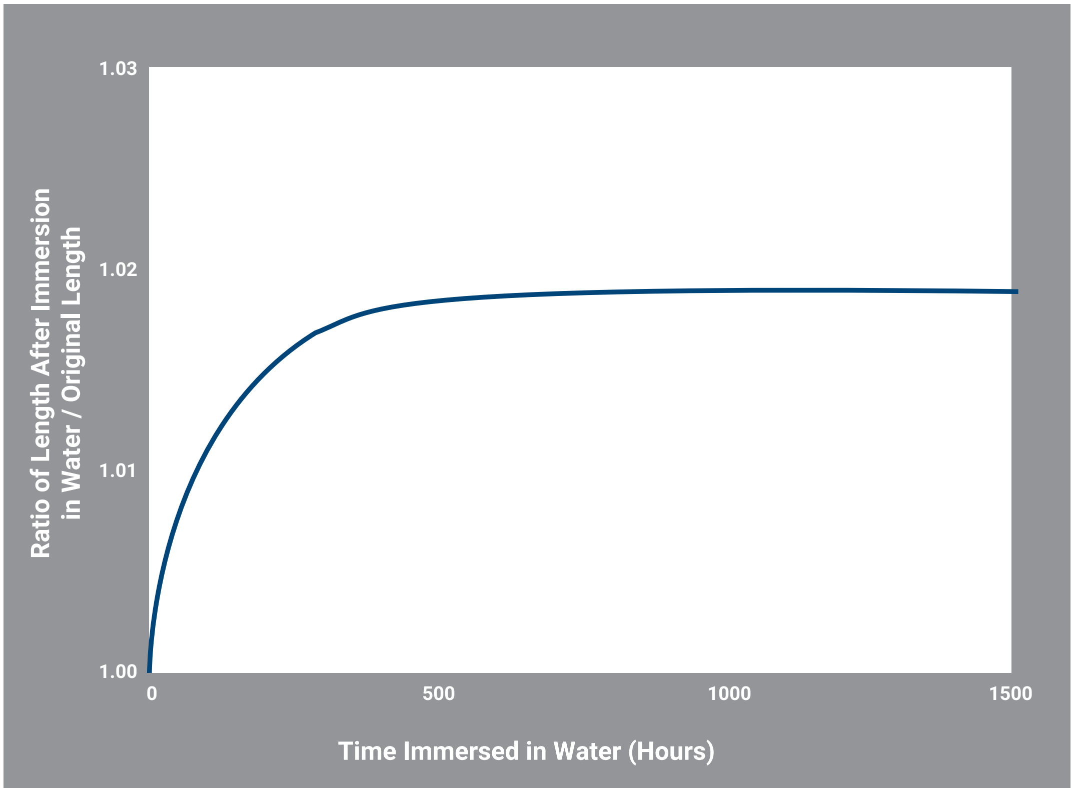
Most plastics will absorb some amount of water when exposed to moisture in the atmosphere or immersed in water during use. Moisture absorption can result in a plastic material swelling, causing parts to go out of tolerance. Nylon is an extreme example in that it absorbs moisture at a higher rate than most thermoplastics. Figures 4 and 5 show changes in mass (Fig. 4) and length (Fig. 5) for a 10 cm long x 5 cm wide x 1.6 mm thick nylon 6 plaque immersed in water. Note that the plaque continued to absorb water until it reached saturation after approximately 400 hours. At saturation, the nylon 6 test specimen increased in mass by 8.8% and it increased in length by 2%.

Figure 4. Changes in Mass for a 10 cm Long x 5 cm Wide x 1.6 mm Thick Plaque of Nylon 6 Immersed in Water at Room Temperature



Source: Adapted from Monson, 2007

Figure 5. Changes in Length for a 10 cm Long x 5 cm Wide x 1.6 mm Thick Plaque of Nylon 6 Immersed in Water at Room Temperature



Source: Adapted from Monson, 2007

It is important that designers allow for changes in the dimensions of a plastic part as the moisture content in the material fluctuates due to contact with liquid water and/or changing levels of atmospheric humidity.

RESIDUAL STRESS

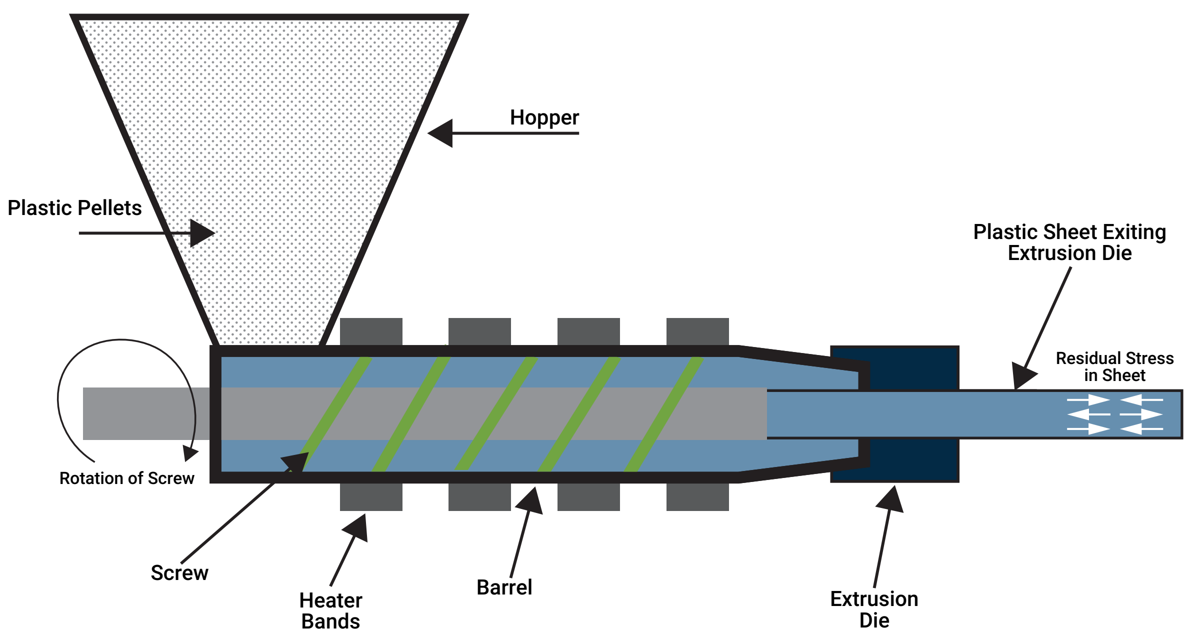
Residual stress refers to mechanical stresses that are internal to a plastic component without external forces acting on the part. Residual stresses can relieve over time, causing a part to warp, crack, or otherwise deform and go out of tolerance.

Residual stress can be introduced into plastic sheet, rod, and tube stock at the time of processing (extrusion, injection molding, or compression molding). Stress can also be introduced during subsequent machining operations.

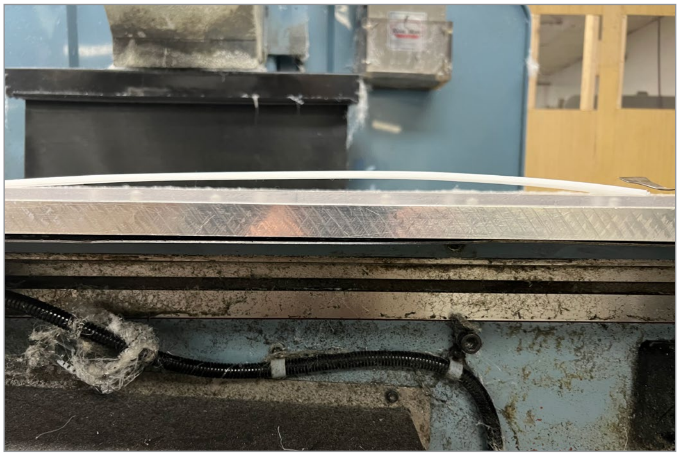
Residual stress in extruded plastic sheet is often due to the rapid cooling of the surfaces of the sheet as the hot plastic exits the extrusion die as shown in Figure 6. Since plastic materials have low thermal conductivity, the center of the sheet continues to cool slowly and it shrinks as it is cooling. However, the plastic in the center of the sheet is constrained to some extent by the frozen material at the surfaces. The different rates of cooling and shrinkage in the center of the sheet relative to the material at the surfaces results in compressive stresses at the surfaces and tensile stresses in the center. A sheet in this highly stressed condition is likely to present challenges during fabrication as the internal stresses relieve, which can result in the plastic changing shape in unexpected ways.

Figure 6. Residual Stress Introduced into a Plastic Sheet During Extrusion

Plastic Sheet Extrusion



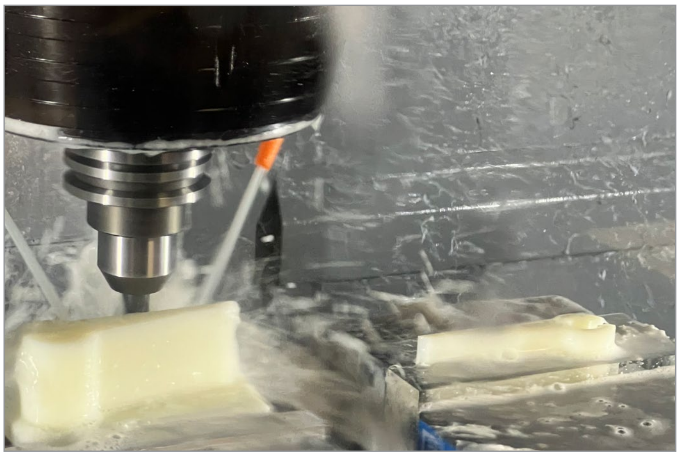
The photos below show a plastic part that warped during machining due to the relief of residual stress in the sheet.




This UHMW-PE wear rail warped during machining due to residual stress in the sheet material.

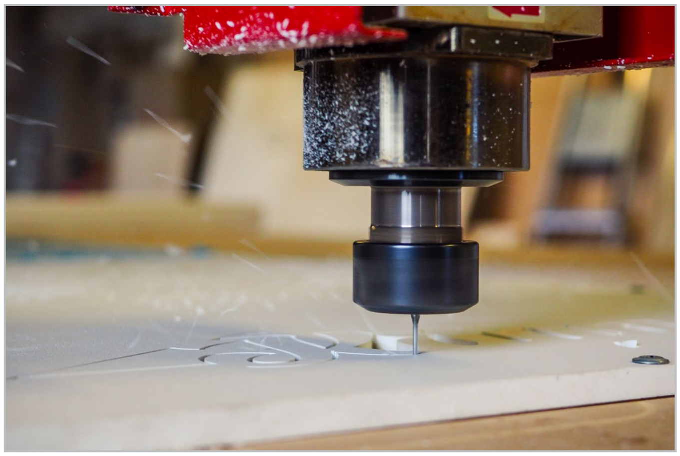
Residual stress in plastic sheet and rod stock can be minimized by carefully controlling cooling rates and other extrusion process settings. Residual stress can be further reduced by putting the material through an annealing cycle, where the stock is slowly heated and then kept at elevated temperature for a period of time, allowing the stresses to relax. The material is then slowly cooled to room temperature. Annealing is especially important for thick sheets and large diameter rods, where stresses tend to be higher.

Machining operations can create residual stress in plastic materials in several ways. Machining generates frictional heat at the surfaces being contacted by the cutting tool. A stream of cool compressed air or a water based cutting fluid can be used during machining to dissipating frictional heat and remove the waste chips generated during cutting.



Water based cutting fluids or cool compressed air can be used to reduce frictional heat buildup and remove chips during machining.

The mechanical action of the cutting tool also strains (deforms) the plastic where the tool contacts the material. Some of the strain is quickly recovered as the material springs back to shape but some degree of residual stress often remains in the plastic. These stresses can later relieve, causing the part to go out of tolerance.

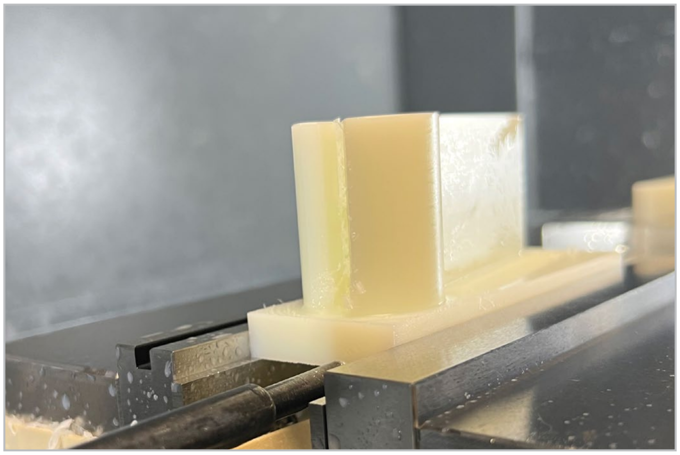


The mechanical action of cutting tools introduces frictional heat to plastic parts and also deforms the parts to some extent during machining operations.

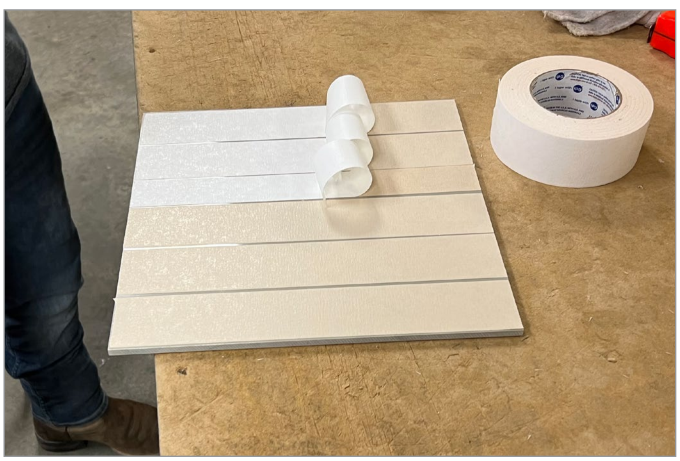
In some cases, where tight tolerances must be achieved, plastic parts can be machined to a rough shape and then allowed to relax for several days. This allows internal stresses to dissipate prior to the parts being machined to their finished geometry. An annealing step can be added prior to final machining if even lower levels of stress are required.

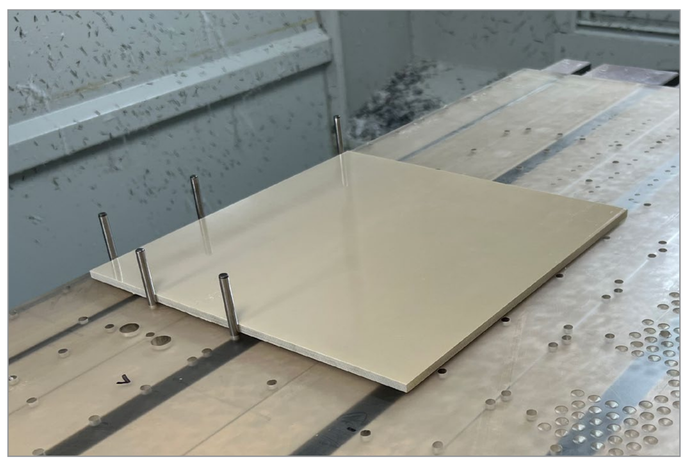
Using sharp carbide or high-speed steel tools with geometries optimized for cutting a particular plastic material can help to reduce stress introduced during machining. Carefully controlling tool RPMs and feed rates will also help to minimize stress.

Fixturing with tight clamps or vises can also create residual stress in plastic parts during machining. One method to mitigate this is to clamp onto sections of the stock shape that will not become part of the finished component as shown in the photo below. The area that was clamped is removed as a last step in the machining process. Double sided adhesive tapes can also be used to fixture plastic stock shapes for machining. Tapes don't introduce stress into stock shapes.



This nylon part was fixtured at a location below the geometry of the finished component to minimize the effect of residual stress from the vise on the finished part.





Double sided tape can be used to fixture plastic parts in order to avoid stress from metal vises and clamps.

CREEP STRAIN

Creep strain refers to plastic materials deforming when subjected to mechanical loads over long periods of time. Plastic parts can change shape and go out of tolerance if mechanical stress is placed on the parts due to improper storage and handling. Creep strain is more pronounced at elevated temperatures and when parts are placed under increased loads. For example, the PVC extrusions shown on the left side of the photo below were improperly stacked in a storage rack for several months during the summer and they deformed due to creep strain.

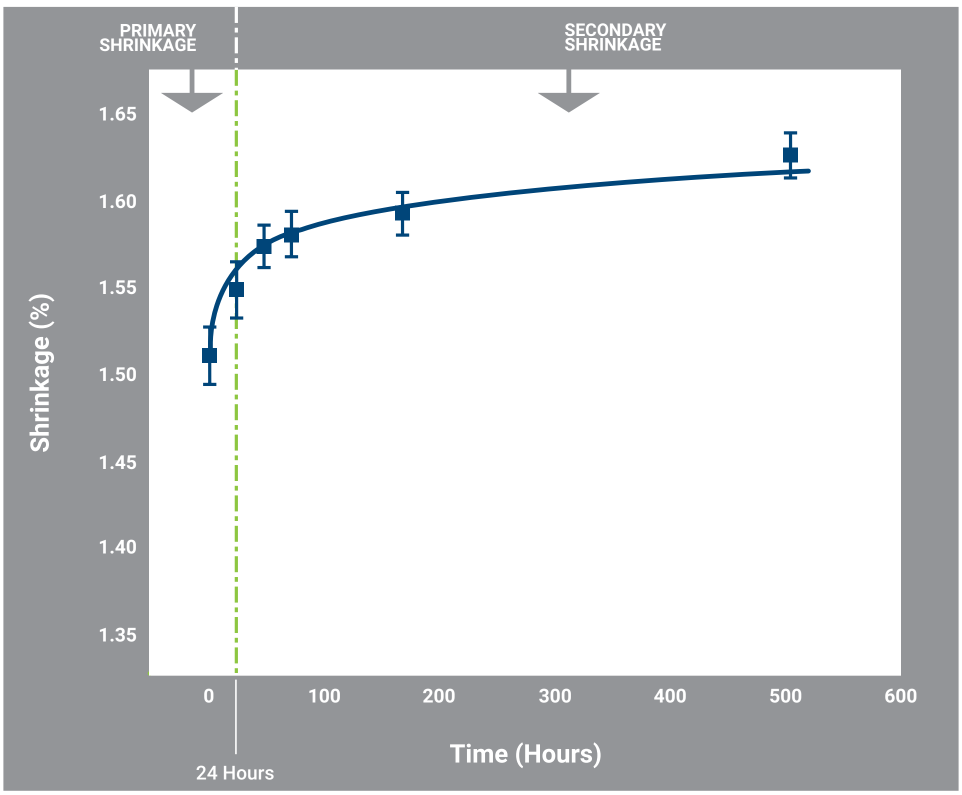
These PVC extrusions warped from creep strain due to improper storage.

POST MOLDING SHRINKAGE

Injection molded parts made from certain semi-crystalline thermoplastics can continue to crystallize and shrink for several days after molding. Semicrystalline plastics can crystallize at temperatures above their glass transition temperature (Tg) and below their melting temperature (Tm). For some polymers such as acetal and polypropylene, room temperature is above their Tg and below their Tm so parts made from these materials can shrink after molding at room temperature (Sepe, 1999).

Figure 7 shows post molding shrinkage for a homopolymer polypropylene test specimen, injection molded with a mold temperature of 80°C. The molded part was conditioned at room temperature (23°C) for 504 hours. After 24 hours, the part had reduced in length by 1.55%. The specimen then continued to crystallize and shrink and after 504 hours, it had reduced in length by 1.63% (Kosciuszko, 2021).

Figure 7. Post Molding Shrinkage of a Homopolymer Polypropylene Test Specimen. 80°C Mold Temperature. Conditioned for 504 hours at 23°C.



Source: Adapted from Kosciuszko, 2021

Post-molding shrinkage can be problematic if injection molded acetal or polypropylene parts are measured for quality assurance before they are truly stable. For example, the acetal component shown in the photo below had dimensions that were within the specified tolerances when it was molded. The part then continued to crystallize and shrink. When the part was measured by the customer, who received it one week after molding, it was undersized and it no longer met the specified tolerances.

This injection molded acetal component exhibited post mold shrinkage, resulting in the part being outside of the specified dimensional tolerances.

Quality management procedures for plastics injection molded from acetal and polypropylene must be designed with post-mold shrinkage in mind in order to avoid rejections.

CONCLUSION

The intention of this paper was to provide an overview of some dimensional stability challenges associated with plastic materials including thermal expansion, water absorption, residual stress, creep strain, and post-molding shrinkage. Being aware of these issues can help to prevent frustration and costly rejections for both specifiers and fabricators.

More information on plastic materials and plastic part design can be found on Curbell Plastics' website (www.curbellplastics.com). For help with plastic application questions, send an inquiry via our online Ask a Plastics Expert form.

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TECHNICAL EXPERTISE

Curbell white papers are intended to provide engineers and designers with basic information about the engineering polymers available as sheet, rod, tube, and film stock from Curbell Plastics. We invite you to contact Curbell via e-mail at **technicalsupport@curbellplastics.com** to discuss applications in detail

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Dr. Keith Hechtel is Senior Director of Business Development for Curbell Plastics. Much of his work involves helping companies to identify plastic materials that can be used to replace metal components in order to achieve quality improvements and cost savings. Dr. Hechtel has over 35 years of plastics industry experience and he is a recognized speaker on plastic materials and plastic part design.

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