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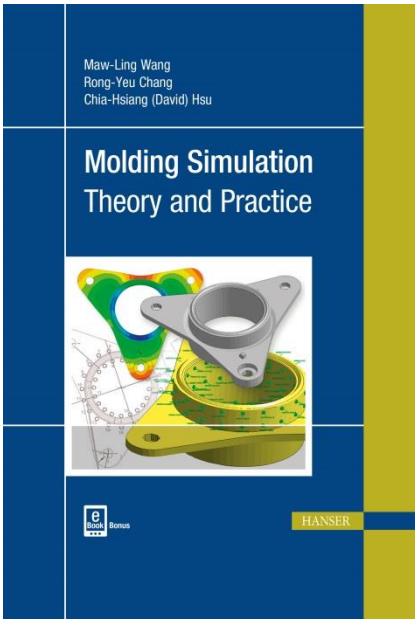

Sample Pages

Molding Simulation: Theory and Practice

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Preface

Injection molding techniques have been developed over decades and well-applied in automotive, 3C (Computer, Communication, and Consumer electronics), optics, medical products, and in daily necessities, among other areas. Due to this long-term development and widely ranging applications, the individual molding criteria have been specialized in several industries to fit various product specifications and innovative materials.

Many industries are producing novel plastic products, such as FRPs (fiber reinforced plastics) replacing metal to reduce weight while maintaining the structural strength of automotive parts. The unique appearance achievable from techniques such as multi-component design of 3C products is more attractive than that from the common design by conventional injection molding. The high turnover rate in mobile products has raised the demand for plastic lenses so that the capacity and profits of the optics industry are ensured as long as production stability of high-precision-shaped lenses can be achieved in multi-cavity molding. Usually, medical plastic products have a high added value, but they especially must pass severe material certification standards at the primary stage, and dust-free or sterile production may be necessary. As for daily necessities, although part dimensional precision is not demanded as much as in other industries, there are still molding issues to consider; for example, conformal cooling method might be evaluated in order to reduce the cycle time.

The increasing requirements and diversity of plastic products demand a shorter time to market. However, much time can be spent in developing the procedures for some products, from concept generation, design drawing, mold tooling and assembling, trial-molding to mass production. “How can the procedures be shortened using CAE (Computer Aided Engineering) tools?” then becomes a key question for industry. The idea is to predict potential molding problems and defects by CAE during the design stage, modify the design according to these results, and then re-analyze until the best design is obtained. Since the 1970s, virtual trial moldings have been implemented by computer using injection molding simulation CAE tools to check whether the molding parameters are good enough for manufacture. These

parameters are part design, gate design, runner layout, cooling layout, molding materials, process conditions, and so on. From CAE, the optimized parameters can be estimated efficiently and provided as the initial-guess settings for the real molding to cost down in time, manpower, material, and energy. To summarize, CAE is a decades-proven design-verification tool for real applications of the injection molding process.

In addition to conventional injection molding, there are many innovative molding processes that have appeared. Characteristics of lightweight parts, low clamping force, and low shrinkage are noted in the G/WAIM (Gas-/Water-Assisted Injection Molding) and MuCell® processes. With co-/bi-injection, multi-component or multi-functional parts can be produced by one-shot molding. The compression operation of ICM (Injection Compression Molding) provides a uniform packing mechanism on a plastic melt that compensates the non-homogeneous packing of injection molding. Metal or ceramic PIM (Powder Injection Molding) is especially adapted to manufacture the green part of highly precise and complicated geometry products. When using a hot runner system, the most important thing is accurate temperature control. Moreover, improvements in plastics molding techniques are not only exhibited in injection processes, but also, for example, in consideration of the resin curing reaction within the multi-substrate molding of an IC package, a process that has evolved greatly.

Molding issues become more challenging and complicated with innovations in processes and materials, which can lead to a longer time and higher cost in conditions optimization. In particular, when fiber composites are involved, obtaining favorable fiber orientations and maintaining longer fiber lengths after processing are extremely important goals, because the microstructures of the materials dominate the product quality. In RTM (Resin Transfer Molding), the microstructures are related to the resin impregnation degree inside the continuous fiber mat or woven roving. The involvement of the effects of surface tension, fiber deformation, and resin curing reaction all make RTM process control more difficult. Fortunately, CAE is nowadays available to simulate these new procedures and as a process innovation tool.

From decades of experience in CAE assistance in molding troubleshooting, we have found that processing knowledge is as important as software operation to CAE users. To make a high-quality molded product, the total effects of part design, mold design and manufacture, machine capability, and material properties must all be taken into account and then integrated into the CAE tool to implement design verification and conditions optimization wisely. Each of these definitely involves a deep knowledge, whether in theory and/or empirical formula. When talking about molding issues, plastics rheology and the designs of part and mold are especially the key criteria since their interactions will dominate the material property variations inside the mold.

At Moldex3D, as worldwide leaders in molding simulation software, we are not just continuously enhancing CAE capability but also intend to help industry people improve their molding-related abilities. The importance of training and instruction has become strongly apparent to us. As a result, this book consists of plastics molding theory, practical applications, and case studies intended to elaborate the molding system and melt flowing behaviors in an easy-to-understand way. The practical examples show how to use CAE to achieve design verification and process innovation in conventional injection molding, G/WAIM, co-/bi-injection, foam injection molding, PIM, RTM, and IC packaging. With this book, readers can effectively learn molding simulation applications and its importance in molding industries.

The CAE case study exercises found in the book for execution in the Moldex3D software can be downloaded from the Website: https://moldex3d.box.com/s/zr6fvc1vlhbi4ocx111jwd3wmxt4ooif, for which the QR code is as follows:

Maw-Ling Wang

Rong-Yeu Chang

Chia-Hsiang (David) Hsu

Table 6.2 Polymer Type versus Clamping Force [3] *(continued)*

Resin	tonnes/in^2	tonnes/cm^2	MN/m^2
AS (SAN) (long flows)	3.0–4.0	0.465–0.62	46.3–61.8
LDPE	1.0–2.0	0.155–0.31	15.4–30.9
HDPE	1.5–2.5	0.233–0.388	23.2–38.6
HDPE (long flows)	2.5–3.5	0.388–0.543	38.6–54.0
PP (Homo/Copolymer)	1.5–2.5	0.233–0.388	23.3–38.6
PP (H/Co) (long flows)	2.5–3.5	0.388–0.543	38.6–54.0
PPVC	1.5–2.5	0.233–0.388	23.3–38.6
UPVC	2.0–3.0	0.31–0.465	30.9–46.3
PA6, PA66	4.0–5.0	0.62–0.775	61.8–77.2
PMMA	2.0–4.0	0.31–0.62	30.9–61.8
PC	3.0–5.0	0.465–0.775	46.3–77.2
POM (Homo/Copolymer)	3.0–5.0	0.465–0.775	46.3–77.2
PET (Amorphous)	2.0–2.5	0.31–0.388	30.9–38.6
PET (Crystalline)	4.0–6.0	0.62–0.93	61.8–92.6
PBT	3.0–4.0	0.465–0.62	46.3–61.8
CA	1.0–2.0	0.155–0.31	15.4–30.9
PPO-M (unreinforced)	2.0–3.0	0.31–0.465	30.9–46.3
PPO-M (reinforced)	4.0–5.0	0.62–0.775	61.8–77.2
PPS	2.0–3.0	0.31–0.465	30.9–46.3

6.1.6 Material Viscosity and Flow Behavior

The basic principle for setting the injection speed and pressure in the filling stage is that high speed and high pressure facilitate the filling to be finished in a short time to avoid fast cooling of the melt, which would increase the flow resistance. The reason for using a high pressure is to avoid a drop of injection speed due to insufficient injection pressure, which may lead to deviation from the original parameter setting.

When the plastic material is flowing, an internal pressure (counteractive force) is generated by the flow resistance as the plastic is compressed. A faster pressure rise denotes a higher flow resistance, and thus the pressure loss from flowing through the part becomes higher. By increasing the melt temperature to reduce the viscosity of the material, the flow resistance can be reduced, and a lower flow resistance in the filling stage leads to a smaller increase of the internal pressure.

Possible causes for a rising flow resistance, leading to high internal pressure and high pressure loss, are as follows: thinner thickness, long flowing distance, lower mold/melt temperature, slower injection speed, and high viscosity.

Because the flow resistance is proportional to the melt viscosity, it is still possible to change the viscosity and reduce the flow resistance in the same mold and same material through modification of the molding conditions. Polymer materials are non-Newtonian fluids and hence their viscosity not only changes at different temperatures but also depends on the shear rate.

To understand the influence of the shear rate on the viscosity of a plastic material, it is necessary to interpret the implication of a viscosity curve of material. The viscosity affects the flow resistance, and then the filling pressure, as well as the specifications and capacity of machine required. The viscosity difference of the plastic material between each region in the mold cavity also affects the pressure transmission, the flow balance, and the follow-up packing pressure transmission, which has a direct relationship to the mass and quality of the part.

Therefore, the quality control of the part is an important factor to understand the relationship between viscosity variation and molding conditions of plastic materials. The viscosity variation of polystyrene (PS) is shown as an example in Figure 6.36.

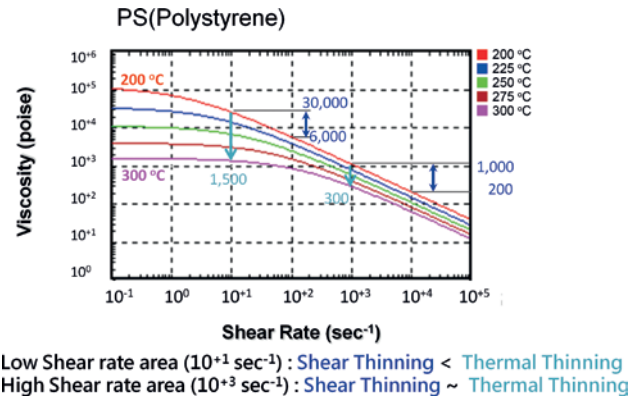


Figure 6.36 Viscosity of polystyrene

In the low shear rate zone where the shear rate is 1.0×10^1 sec^{-1} and the temperature is 200 °C, by increasing the temperature from 200 to 300 o, the viscosity is reduced from 30,000 poise to 1500 poise. By increasing the shear rate from 1.0×10^1 sec^{-1} to 1.0×10^2 sec^{-1}, the viscosity can be reduced from 30,000 poise to 6000 poise. Therefore, the influence of the shear rate on the viscosity is relatively smaller than the influence of the temperature.

In the high shear rate zone where the shear rate is 1.0×10^3 sec^{-1} and the temperature is 200 °C, by increasing the temperature from 200 to 300 °C, the viscosity is reduced from 1000 poise to 300 poise. By increasing the shear rate from 1.0×10^3 sec^{-1} to 1.0×10^4 sec^{-1}, the viscosity can be reduced from 1000 poise to

200 poise. Therefore, the influence of the shear rate on the viscosity is close to but slightly larger than the influence of the temperature on the viscosity.

Regarding various effects of viscosity, the viscosity curves of three different groups of plastic materials are compared in Figure 6.37 to explore the sensitivity of viscosity versus temperature and shear rate.

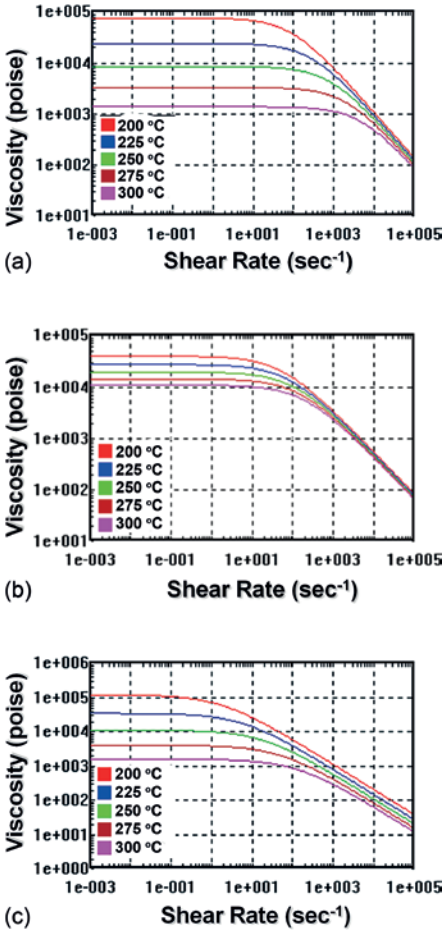


Figure 6.37 Viscosity: (a) temperature sensitive, (b) shear rate sensitive, and (c) temperature and shear rate sensitive

Figure 6.37(a) shows a bigger gap between each temperature curve, indicating a significant effect on decreasing the viscosity by raising the temperature but an insignificant effect on decreasing the viscosity by raising the shear rate, which shows that the viscosity of the material is sensitive to temperature. Figure 6.37(b) shows a smaller gap between each temperature curve, indicating an insignificant effect on decreasing the viscosity by raising the temperature but a significant effect on

decreasing the viscosity by raising the shear rate, which shows that the viscosity of the material is sensitive to shear rate. Figure 6.37(c) shows a bigger gap between each temperature curve and also the decrease of viscosity with the increase of shear rate is significant, which shows that the viscosity of the material is sensitive to both temperature and shear rate.

Figure 6.38 shows a comparison of the injection pressure under different melt temperatures (250 and 280 °C) for polymethylmethacrylate (PMMA). As the melt temperature rises, the viscosity of the material drops and thus leads to a decrease of the flow resistance as well as the injection pressure. When the melt temperature is 250 °C and the filling time is 1.0 sec, the injection pressure reaches 100 MPa; when the melt temperature is 280 °C and the filling time is 1.0 sec, the injection pressure reaches 70 MPa.

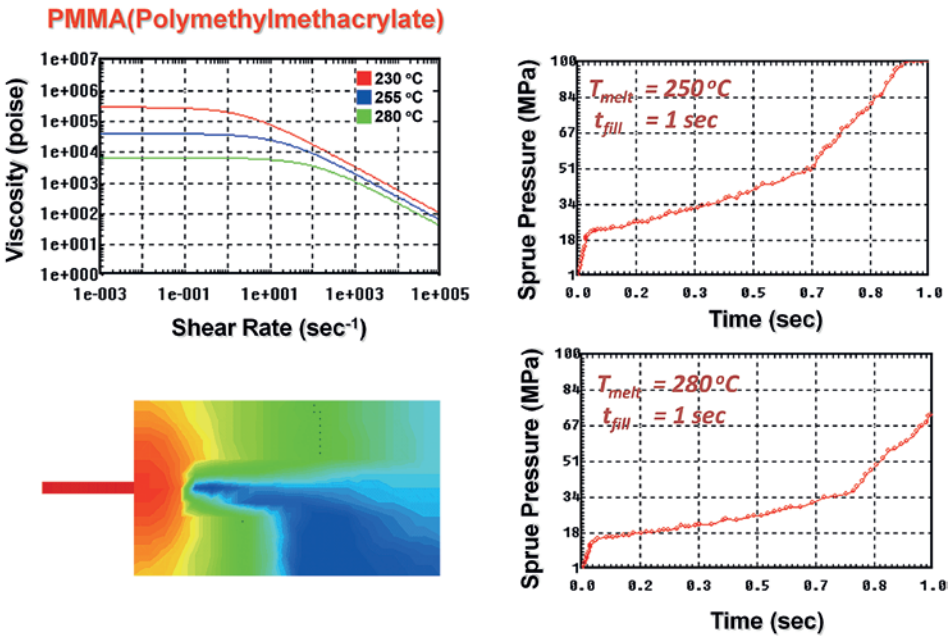


Figure 6.38 Melt temperature versus injection pressure

Different materials have different viscous characteristics. The influence on the injection pressure of three different plastic materials is compared in Figure 6.39. By setting the same filling time at 1.0 sec, the injection pressure for polypropylene (PP) is 32 MPa, and 28 MPa for polystyrene (PS), whereas polymethylmethacrylate (PMMA) requires 100 MPa to complete the filling process. Furthermore, when the filling time reaches 0.8 sec for PMMA, the pressure already hits the upper limit of 100 MPa, which indicates that the pressure control mode already kicks in and the system cannot maintain the original fixed flow rate for filling.

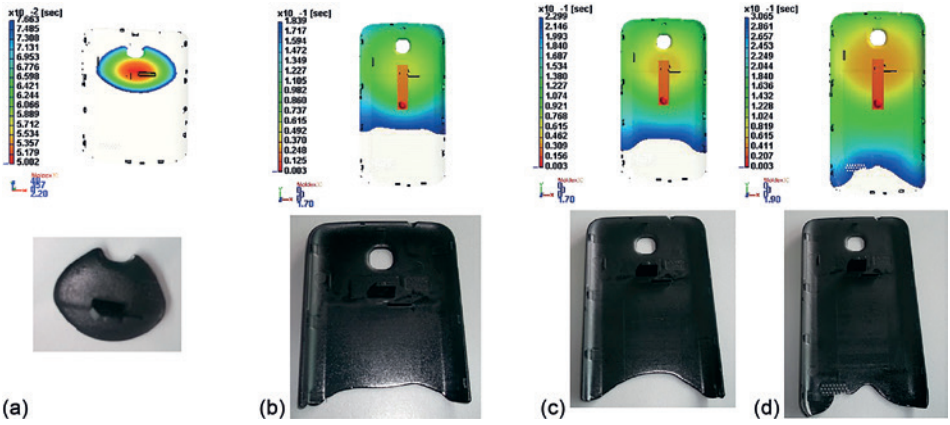


Figure 6.42 Consistency between CAE analysis and experiment in melt front time

The surface quality of an actual part can also be assessed through an analysis result. For example, by observing the surface quality of the injection-molded part as shown in Figure 6.43, a significant mark defect is seen at the boundary between the thickness of 0.7 mm and 1.0 mm in the center, where a considerable shear stress difference also exists.

Figure 6.43 Mark defect versus shear stress

As shown in Figure 6.44, the surface quality of the part can be improved by changing the thickness of the design. Figure 6.44(a) is the original design and Figure 6.44(b) is the revised one. The main change is to design a smooth thickness transition area at the boundary where the thickness of 0.7 mm and 1.0 mm meet.

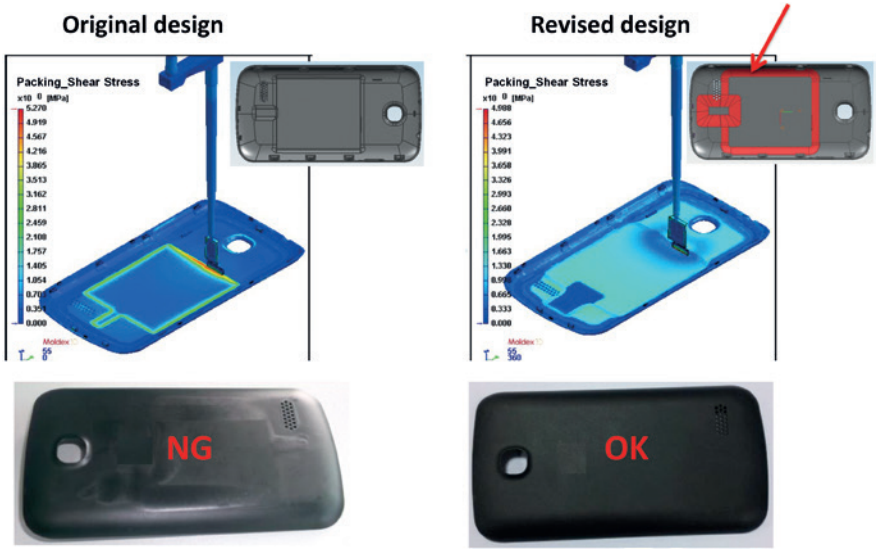


Figure 6.44 Broaden the thickness transition area

From the packing result of shear stress distribution analyzed by CAE as well as the picture showing the part surface, the frame-shaped distribution of shear stress in the central area no longer exists, and the actual surface quality of the part is indeed significantly improved.

6.2.2 Flow Rate Effect on Injection Pressure of Laptop Product

Concerning the injection stroke setting, the runner stroke and the mold cavity stroke are calculated respectively. The runner stroke can be converted from the runner volume, and the mold cavity stroke can be estimated by using 60–90% of the mold cavity volume. Figure 6.45 shows an example using Moldex3D to describe how a multi-step flow rate setting is configured (reference example). The specifications are listed as follows:

Part model: D part of a laptop PC (bottom plate)

Part volume: 122.16 cm^3

Part dimensions: 315 mm × 225 mm × 20 mm

Main thickness: 2 mm

Material: PC/ABS

Runner system: hot runner

Capacity of injection molding machine: 450 tons

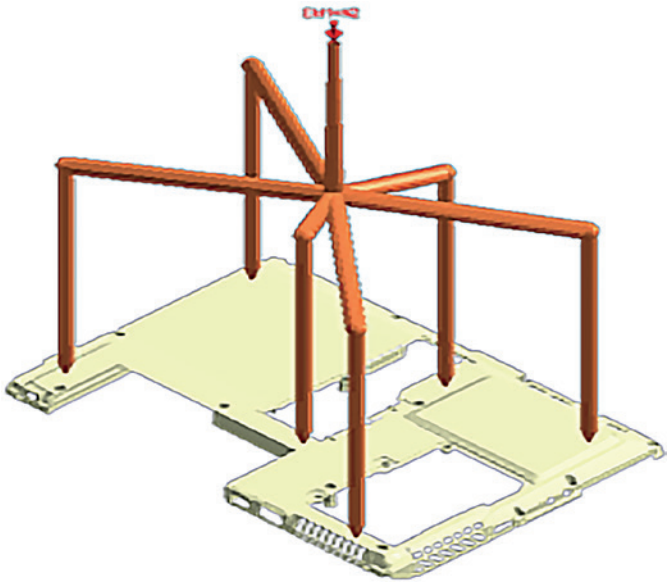


Figure 6.45 Product model

Figure 6.46(a) shows a single flow rate and Figure 6.46(b) illustrates a multi-step flow rate.

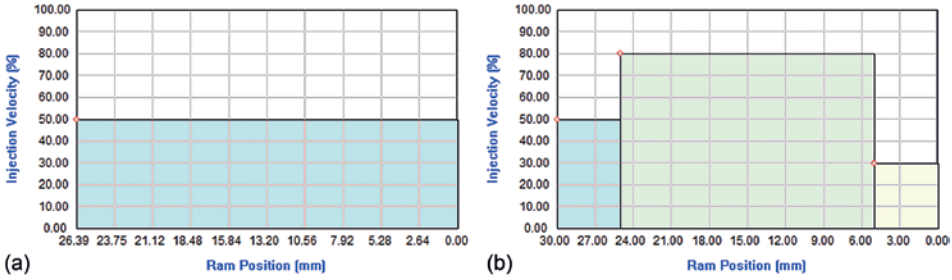


Figure 6.46 (a) Single flow rate and (b) multi-step flow rate

By examining the relationship of flow rate setting to injection pressure and shear rate at the gate as shown in Figure 6.47(a), where the red line denotes a single flow rate, while the blue line denotes a multi-step flow rate, it is found that a multi-step flow rate is able to reduce pressure loss effectively. Also in Figure 6.47(b), where the red line denotes a single flow rate, while the blue line denotes a multi-step flow rate, a multi-step setting is able to reduce the shear rate at the gate as well.

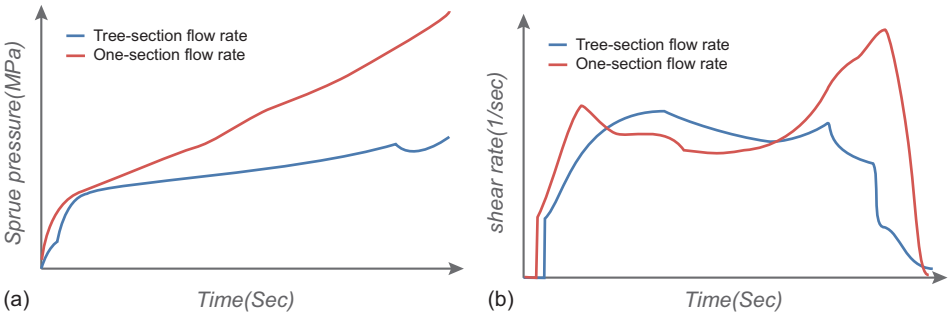


Figure 6.47 (a) Sprue pressure and (b) shear rate

6.3 CAE Case Study

Following the discussions of this chapter and the corresponding CAE verification case, an exercise model, as illustrated in Figure 6.48, is provided in this section for readers to practice CAE application in runner and gate design.

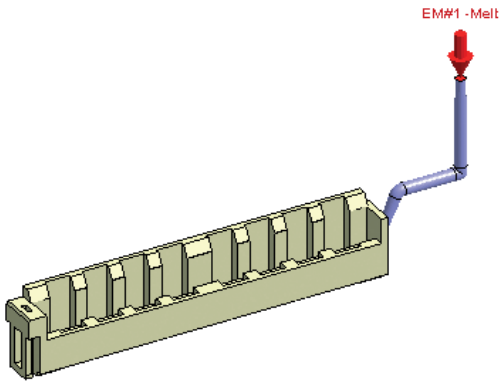


Figure 6.48 Case study sample

Please download the analysis files for CAE Case Study 6.3 from the following website:

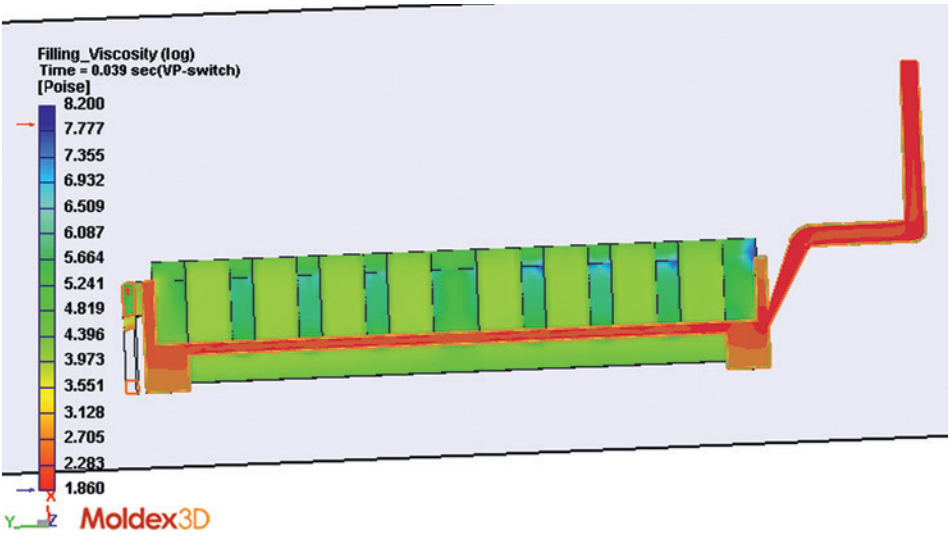
https://moldex3d.box.com/s/zr6fvc1vlhbi4ocx111jwd3wmxt4ooif

Then open the .m3j or .mvj file in Moldex3D and answer the questions below according to the analysis results.

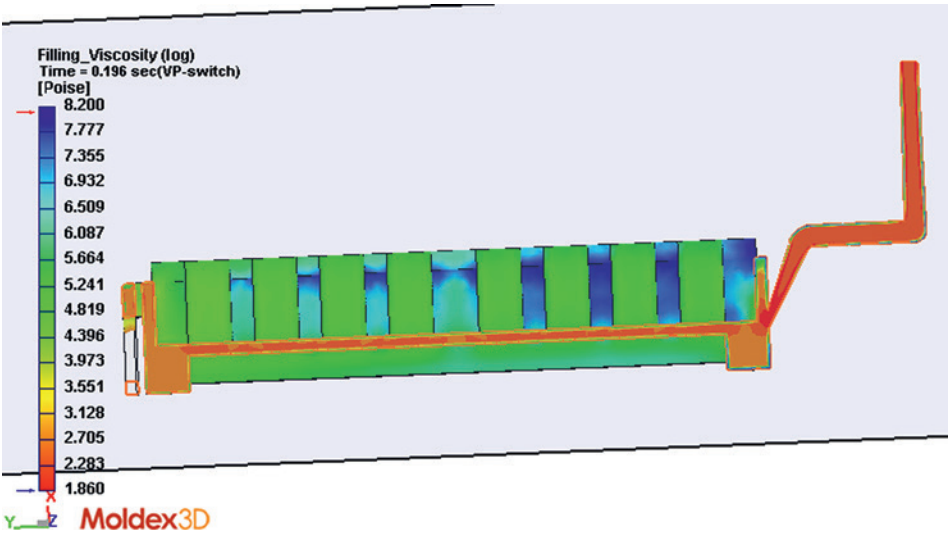
Questions:

1. Pre-analysis of the model
   a) What is the maximum L/t of the case? If taking PA6 as the material, does short shot occur? Why?
   b) Where will be the filling ends and weld lines?
2. Comparison of different plastic materials
   a) Run the simulations of flow analysis with "PA Ultramid 8202 BASF" and "PC+ABS CYCOLOY C7410 SABIC(GE)". Why is the sprue pressure of PC+ABS much higher than that of PA? Try to explain the reasons with the comparison function of material wizard.
   b) What makes the differences in the simulation results of viscosity and shear stress at EOF (end of filling) between PA and PC+ABS? Try to explain the reasons with respect to material properties.
   c) Explain how the high-viscosity material affects the molding results, including molding processes and product quality.
3. Comparison of different process conditions: filling time
   a) The default filling time is 0.1 sec. Compare the sprue pressure results for different filling times from 0.04 to 0.2 sec. Here we set a single flow rate profile. (Hint: check the XY-plots of sprue pressure curves.)
   b) Figure 6.49 shows the internal viscosity results of filling time of 0.04 and 0.2 sec. Why does the viscosity distribution differ with the filling time? (Hint: check the temperature distribution.)
4. Comparison of different process conditions: flow rate
   a) The default flow rate is three-segment profile. Compare the XY-plots of sprue pressure curves of different flow rates with single- and three-segment profiles.
   b) Compare the shear rate distributions at the gate of different flow rates with single- and three-segment profiles (by clipping function).
5. Comparison of different process conditions: VP switch
   a) The default VP switch is at 98% filling volume. Compare the XY-plots of sprue pressure and clamping force curves of different VP switch points at 90%, 98%, and 99% filling volume. Try to explain the reasons for the difference.
   b) Compare the locations of weld line and welding temperatures. Try to explain the reasons for the difference.

6. Comparison of different wall thicknesses
   a) Compare the XY-plots of sprue pressure and try to explain the reasons for the difference.
   b) Try to catch the melt front time result with the set perspective of 90, 0, 90 on "view control panel" to show the filling difference caused by thickness change.
   c) Compare the shear stress distributions at EOF and try to explain what kind of bad influence to the part might be caused by changing thickness.



(a)



(b)

Figure 6.49 Internal viscosity results (by the clipping function with the plane of z = 1) at VP switch for the filling time of (a) 0.04 sec and (b) 0.2 sec

9.1.1 The Causes of Warpage

There are various reasons for warpage, including geometric factors such as part design, insert effect, process conditions including pressure and temperature, and material properties such as fibers and Pressure-Volume-Temperature (PVT) behavior. In order to resolve warpage, identifying the cause(s) is critical. Normally a fishbone diagram, as shown in Figure 9.5, is used to list all possible causes for warpage, which then can be compared with the real case to narrow down the source.

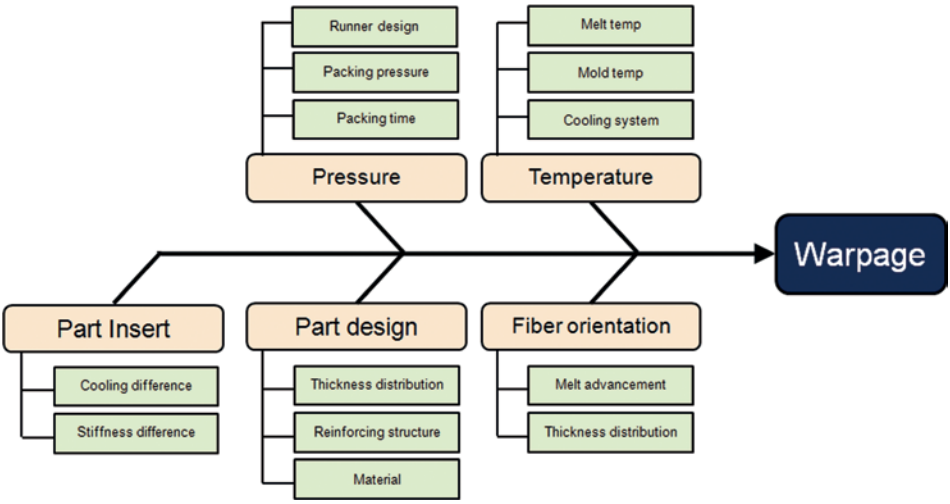


Figure 9.5 Fishbone diagram for warpage troubleshooting

1. Material

The plastic properties affecting shrinkage and warpage include plastic type, degree of crystallization (crystallization rate), and filler properties. Shrinkage behavior varies between different plastic types. For example, polyoxymethylene (POM) is a highly crystallized material and presents significant shrinkage after ejection. Polypropylene (PP), on the other hand, has a relatively minor shrinkage. Amorphous polymers such as poly(methyl methacrylate) (PMMA) have the lowest shrinkage rates. The crystallization rate is related to cooling. Nylon is a material with a low crystallization rate compared to the short injection filling time. The cooling is too fast for a high relative degree of crystallization, which leads to further shrinkage even after mold release. Fillers (inorganic substances) are basically rigid and do not shrink substantially, which makes them ideal for improving the mechanical properties and lowering the shrinkage of the polymer matrix. However, the induced viscosity increase in the melt poses challenges to processing with high filler content.

2. Part Design

Regarding the design of parts and molds, as heat tends to accumulate in the center area of the wall thickness, this area tends to shrink more after the packing pressure is released. The constantly dropping temperature would cause volumetric shrinkage in the original high-temperature areas. A single flat plate does not warp as the shrinkage on both sides is the same; however, warpage may occur if ribs are designed on one side. Usually, the ribs cause more shrinkage due to heat accumulation, such that the plate then bends toward the rib side. In some cases, inclusions such as glass fibers when properly aligned may reduce the rib-side shrinkage so that the warpage direction is opposite to the unfilled one. In the following sections, the mechanisms of how ribs, screw boss, and gussets affect warpage will be introduced.

Inserts are normally made of metal, which is stiffer than plastic, and act as reinforcements. Usually, they decrease the warpage. In some cases, an asymmetric shape of inserts may cause non-uniform shrinkage leading to warpage.

3. Mold Design

As for the mold design features, the gate location affects the packing effect in the part, and an irregular pressure distribution would lead to non-uniform shrinkage and cause warpage. How gates affect pressure distribution will be discussed later.

A good design of cooling channels effectively removes heat away from the part, and also homogenizes the temperature. Warpage is less significant if the temperature becomes uniform. But due to the spatial limitations of the mold (avoiding sliding blocks and ejection pins), the arrangement of cooling channels is often less than ideal. Also, the contact between the mold metal and mold mechanisms is unlike one block of material and thus does not conduct heat so well. On the other hand, some molds utilize high thermal conductivity metals such as beryllium copper to better transfer heat from the hot areas to the cooling system. This allows a shorter cycle time and provides a more uniform temperature distribution.

4. Process

Among all the molding process parameters, temperature and pressure are the most important ones to affect warpage because they relate directly to material shrinkage, i. e., PVT behavior. In addition, the faster the injection speed is, the higher the pressure becomes and so the temperature becomes more uniform, as the time it takes for a plastic material to flow from the gate to the end is shorter.

In the packing stage, the controllable parameters are packing pressure, packing time, multi-stage packing, cooling time, and cooling rate. These are all critical factors that affect shrinkage and warpage. During the filling, packing, and cooling stages of plastic molding, as the temperature and pressure keep changing and are

distributed non-uniformly, the density also varies with time and among different areas of the part, leading to non-uniform shrinkage eventually.

The injection molding process can be understood by the changing history of temperature and pressure, the most important causes for part warpage. As shown in Figure 9.6 and Table 9.1, the pressure rises in the filling stage from 1 to 4 along with the occurrence of high packing pressure from 2 to 3 and shear heating from 3 to 4. The cooling stage is from 4 to 5, in which the pressure also decreases. A dynamic process like this changes the density throughout the whole process and complicates the material shrinkage behavior.

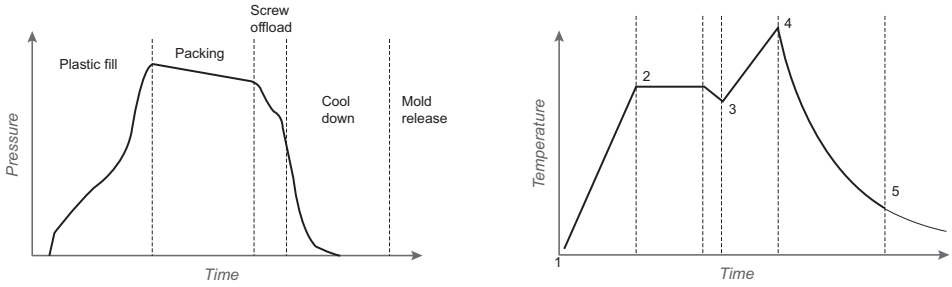


Figure 9.6 Pressure and temperature history of an injection molding process

Table 9.1 Stages of an Injection Molding Process

Stage (see Figure 9.6)	Description
1→2	Plastic enters the barrel and is heated up quickly
2→3	Plastic heats up until melted fully while maintains constant temperature
3	Plastic enters the screw to be heated up by a shear friction
3→4	Injection molding at high speed. Severe shear friction causes even higher temperature
4→5	Injection completes and the materials are cooled down through mold wall
5	Demolding

9.1.2 Material Effects

In addition to pressure, the molecular chain orientation also contributes to non-uniform shrinkage in the part. Both amorphous and semi-crystalline materials are stretched in the flow field when the temperature becomes higher than the phase-transition temperature including T_g or T_m (Figure 9.7 and Figure 9.8). The stretched chains tend to retract back to their most relaxed state with a globular conformation. If the material is frozen because of the fast cooling near the surface, the

strong tendency of the chain to retract causes a larger shrinkage along the flow direction than perpendicular to it. The difference of shear rate leads to a change of the orientation through the thickness. The shrinkage thus becomes anisotropic. If a flow is complex, the shrinkage will not be symmetric across the thickness direction. This will lead to unpredictable warpage for the part; hence, the first step to improving warpage is to simplify the flow. Materials with fibers show even more complex shrinkage behaviors along the direction perpendicular to flow compared to simple polymer chains, as the shrinkage of fibers is different to that of the resin. Warpage is even more complex when the cooling rate of a crystalline material differs, because the induced degree of crystallization and crystalline structure are different so the shrinkage distribution becomes even more unpredictable.

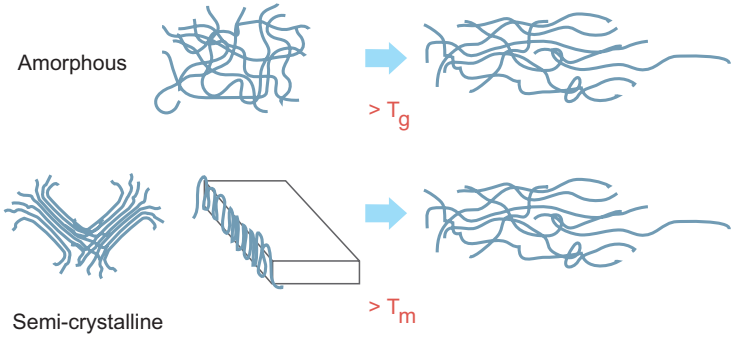


Figure 9.7 Amorphous and crystalline polymers

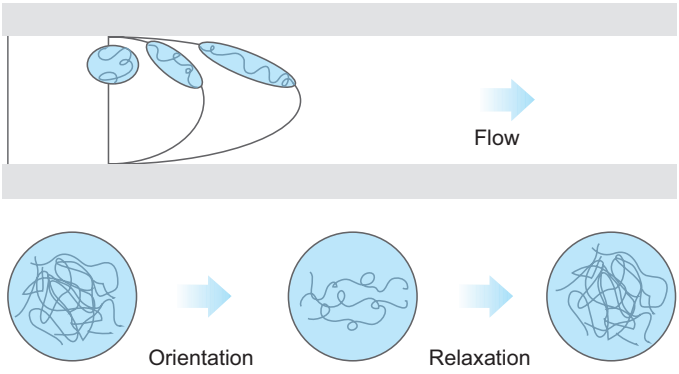


Figure 9.8 Molecular chain orientation caused by a shear flow of fountain flow

Since fibers cannot be stretched, they respond to shear flow by orientation along the flow direction. A simple shear flow results in a uniform orientation, but for fountain flow between the mold walls in injection molding, as shown in Figure 9.9

and Figure 9.10, fibers tend to align along the flow direction near the surface whereas they become perpendicular at the center of thickness area. This anisotropy leads to differential shrinkage between the layers of the part. If the orientation is unsymmetrical between the top and bottom shell layers, non-uniform shrinkage occurs and the part may start to warp.

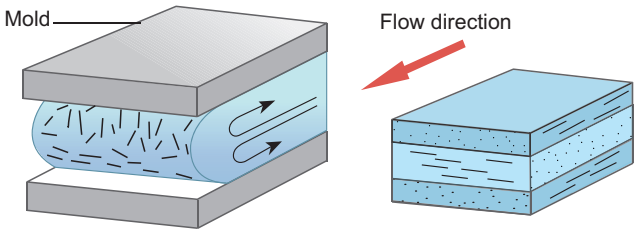


Figure 9.9 Fiber orientation caused by fountain flow

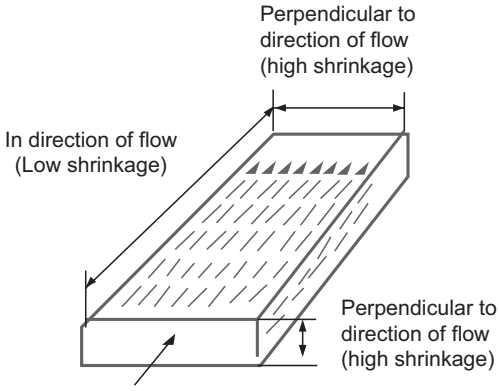


Figure 9.10 Fiber orientation effect on different part shrinkage parallel and perpendicular to the flow direction

Figure 9.11 shows different warpage behavior of an exemplary ribbed plaque caused by different flow directions for the ribs. When the melt enters the plaque parallel to the rib direction, the ribbed half shrinks less so the part shrinks downward. A flow perpendicular to the rib direction leads to an upward shrinkage instead.

Apart from the influence of the flow on the orientation of the molecular chains of the plastic material, the occurrence of warpage is also related to shrinkage behavior. A PVT diagram explains the shrinkage properties of a plastic (Figure 9.12; see Section 2.3.3 for more details). The crystalline material has a sharper transition caused by crystallization during cooling and its shrinkage ratio is higher compared to an amorphous material.

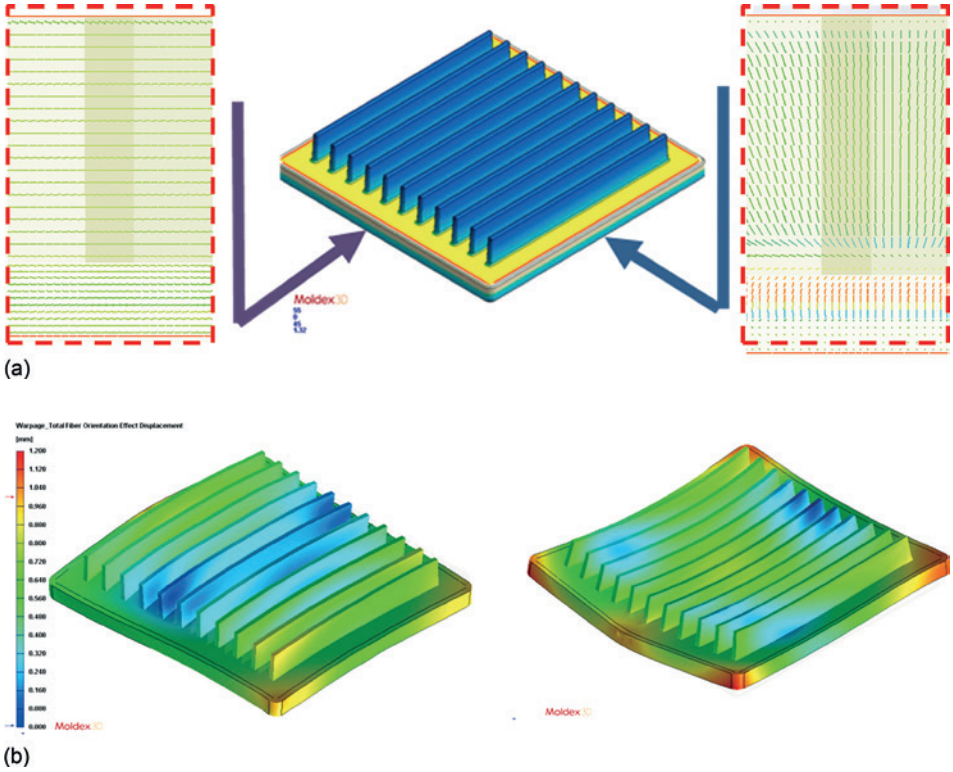


Figure 9.11 (a) Fiber orientation results in the rib section of a plaque with multiple fins. Two gate locations lead to either parallel flow or cross flow inside the fin. (b) The different fiber orientation of fin area leads to different warpage patterns

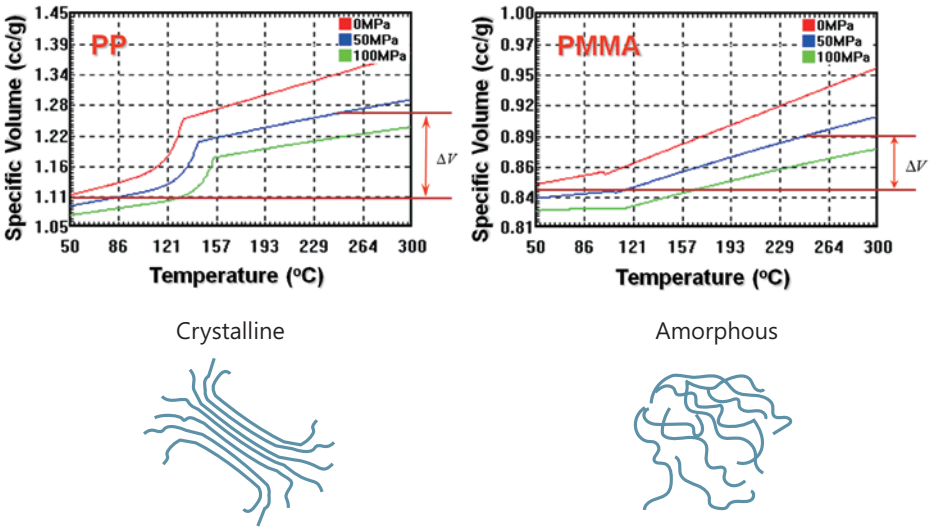


Figure 9.12 PVT diagrams of crystalline and amorphous plastic materials

9.1.3 Geometrical Effects

In Chapter 3 of this book ("Part and Mold Design"), we have introduced part design principles that focus on the part geometrical effect on the flow of plastic as well as the orientation of molecular chains and fibers, and their result on the anisotropic shrinkage. More details about geometrical effects on warpage are discussed here. Since thickness changes in a part are inevitable, the wall thickness needs to be made as uniform as possible for continuous and gradual change. As shown in Figure 9.13, a smooth transition reduces the internal stress caused by a discontinuity of volume shrinkage.

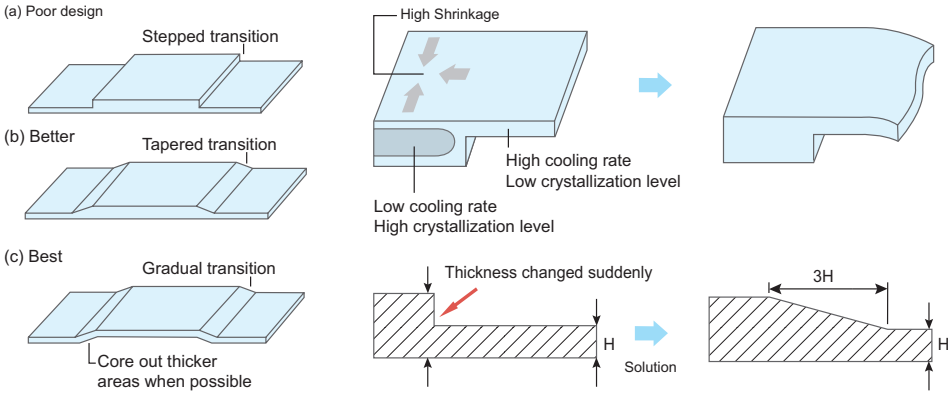


Figure 9.13 Effect of thickness on warpage: a gradual change of thickness is preferred in preventing warpage

As cooling is slower for thicker parts, for crystalline plastics, a slower cooling would generate a higher degree of crystallization in a larger area, which results in higher shrinkage. For thin parts, a high flow rate and the shear effect lead to a more significant orientation along the flow direction, which results in a higher internal stress and more severe warpage.

For a flat plate or box-shaped product, features such as ribs and bosses are often used to reinforce the part. But, as shown in Figure 9.14, ribs also tend to cause unpredictable results of warpage. If the spacing between the ribs is too small to allow enough cooling channels to pass through, the ribbed area would accumulate heat and induce warpage. For mold makers, it is thus preferred to evaluate the warpage level from a molding simulation based on the materials used, the gating location, and the design of the cooling channels.

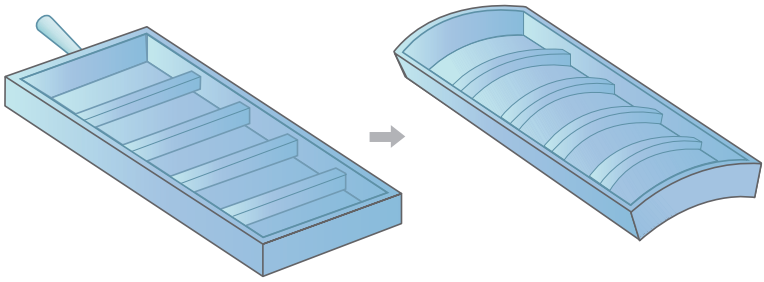


Figure 9.14 Effect of reinforcing rib on warpage: necessary core-out or cooling should be performed to prevent warpage

Cutting ribs into sections is one way of easing warpage. As shown in the top design of Figure 9.15, the bottom of the part is thicker, thus having a higher shrinkage. The thinner ribs do not shrink as much as the bottom so a concave shape is the result. Below are improvements that can eliminate this warpage, including cutting off the consecutive plane on the upper part, which restrains the shrinkage, or the rib can be designed more symmetrically so that the warpage would not be significant while the stiffness can still be maintained.

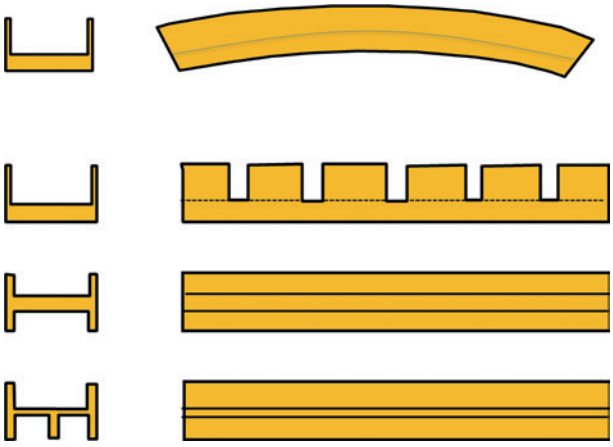


Figure 9.15 Top: uneven thickness distribution leads to warpage; below: improved rib designs to eliminate warpage

When fiber-reinforced plastics encounter a change in thickness, a strong elongational flow orients the fibers as shown in Figure 9.16. The fibers orient better as the flow passes from thick to thin areas as in a converging flow. The effect of this stretching in changing the fiber orientations is stronger compared to shear flow. This is another source of inducing anisotropy into the part apart from shear flow. Parts gated at the center have a strong diverging flow at the beginning of filling. This often leads to a bowl- or dome-shaped warpage.

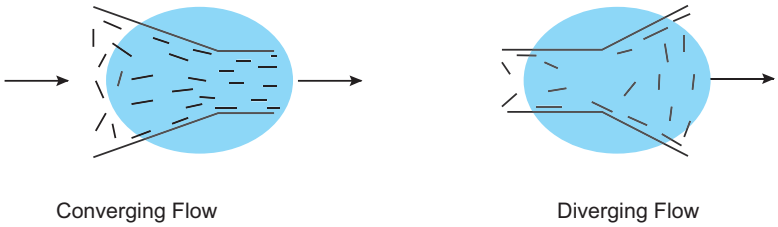


Figure 9.16 Comparison of fiber orientation during converging and diverging flow

9.1.4 Process Condition Effects

Temperature and pressure are the main causes that induce shrinkage. Six factors can be defined in comparison to site conditions: melt temperature, mold temperature, injection speed, packing pressure, packing time, and cooling rate. It is very difficult to test these six factors by trial and error; therefore, we should first understand how they affect shrinkage.

Normally a reduction of shrinkage can be achieved by lowering the melt temperature, increasing the packing pressure, and prolonging the packing time, whereas the mold temperature and injection speed have limited effect on shrinkage. In a cooling process, the mold temperature would not play a critical role unless a material of slow crystallization rate is used, or the mold temperature is too low causing early cooling and insufficient crystallization. The injection speed affects temperature and pressure indirectly. Normally the dynamic range of the injection speed of the machine is not wide, and so is the allowed injection speed range for the part. Therefore, the injection speed, melt temperature, and pressure can all be managed within an adjustable range.

The molding parameters of filling should control the rheological behavior of the plastic material: how much time it needs for filling, and how much pressure should be used for injection. If the injection pressure cannot be evenly distributed in the part, a significant difference in volumetric shrinkage will occur despite applying an excessively high pressure. A localized high injection pressure easily turns into residual stress which deteriorates the part. An ideal injection process ensures that enough material enters the cavity and that the subsequent packing pressure compensates for the shrinkage caused by material cooling. Refer to Chapter 6 for details regarding the effect of pressure on product shrinkage.

Regarding temperature, the shrinkage grows as the temperature of the melt increases. If the melt temperature is too low, the gate will freeze too early rendering the subsequent packing useless. The mold temperature can further be controlled independently via two mold temperature controllers on the two sides of the part

separately. This allows warpage to be actively controlled by manipulation of the part shrinkage on both sides. As shown in Figure 9.17, generally the cooling efficiency of the mold core is poor and the shrinkage is high. To solve the problem, the temperature of the mold core can be lowered to ease the shrinkage, while increasing the temperature of the cavity side for better surface quality.

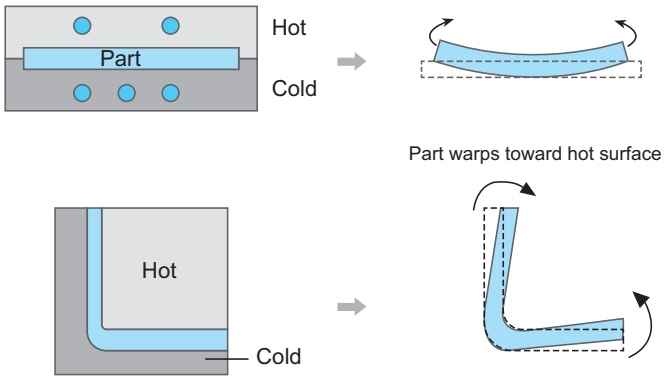


Figure 9.17 Part warpage tendency due to global or localized mold temperature difference

9.1.5 Criteria of CAE Warp Analysis

According to the above principles, CAE can be used for warpage analysis to assess (1) uniform cooling and mold temperature distribution, (2) effective packing before gate freezes, (3) shrinkage due to part geometry, (4) fiber orientation effects on warp, and (5) displacement/flatness prediction:

1. Uniform Cooling and Mold Temperature Distribution

As the cooling channel suitable for both mold cores and mold cavities is different, the induced difference in cooling efficiency would result in distinct shrinkage. It is hard to install a cooling channel at the corner of the mold core, and thus the shrinkage becomes higher. It is thus often seen in box-like parts that the shrinkage at corners is more serious, showing a concave condition around the corners.

In the Moldex3D software, the “Mold temperature difference” function can be used to visualize the difference in mold temperature. Generally, a difference is preferred but which shall maintain a uniform and constant value. The cross-sectional view of the mold temperature could help the user find the problematic hot spot. As shown in Figure 9.18(a), the center of this exemplary fan part shows high temperature even after cooling, which results in notable warpage at the blades (Figure 9.18(b)). If cooling channels can be applied to this side, the warpage can be reduced.

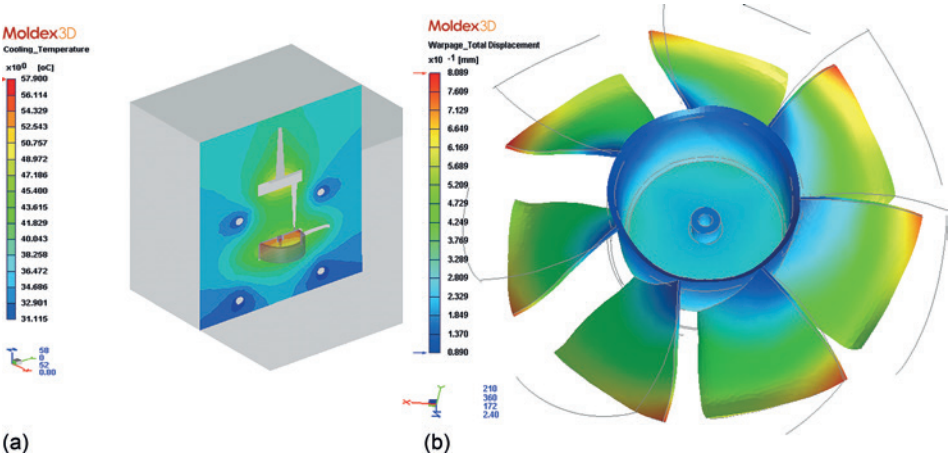


Figure 9.18 (a) Mold temperature cross-section CAE results showing heat accumulation on the core side, and (b) warpage of the part

2. Effective Packing before Gate Freezes

Gate freezing has a key effect on the success of packing. If the gate seals due to cooling, even a higher packing pressure will not contribute to the effectiveness of packing. Therefore, whether the gate is sealed or not should be particularly observed in a simulation analysis. It can be seen from the temperature distribution chart shown in Figure 9.19 that the high-temperature area (green) locates around the middle of the runner, while the temperature is lower at the gate and inside the part, which means that the pressure cannot be effectively transferred into the part if the packing is done from the right side (Figure 9.19).

Description	
Polymer	PA66
Grade Name	6210GC
Producer	NanYa
Comment	
Last modified date	2010/08/25
Process conditions	
Melt temperature (minimum)	270 °C
Melt temperature (normal)	285 °C
Melt temperature (maximum)	300 °C
Mold temperature (minimum)	60 °C
Mold temperature (normal)	80 °C
Mold temperature (maximum)	100 °C
Ejection temperature	210 °C
Freeze temperature	240 °C

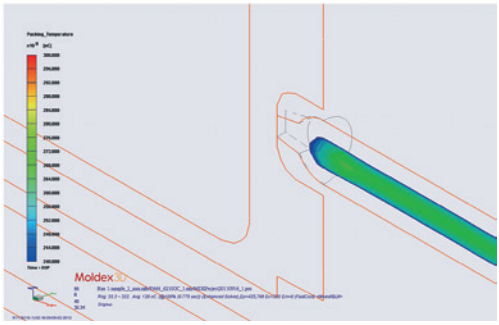


Figure 9.19 Effective packing before gate freezes

3. Shrinkage Due to Part Geometry

Shrinkage difference due to the thickness and geometry characteristics of a part can also affect how a molded part warps. Figure 9.20 shows a slicing of volumetric shrinkage extracted from Moldex3D for a connector case, where its thickness is distributed unevenly. Thicker sections have larger volumetric shrinkage than thinner regions, because heat accumulates more easily in the thicker section, as it is more difficult for cooling to reach the middle area. Because of the uneven thickness distribution, the volumetric shrinkage varies. Therefore, a well-considered part design is an essential point to prevent product warpage.

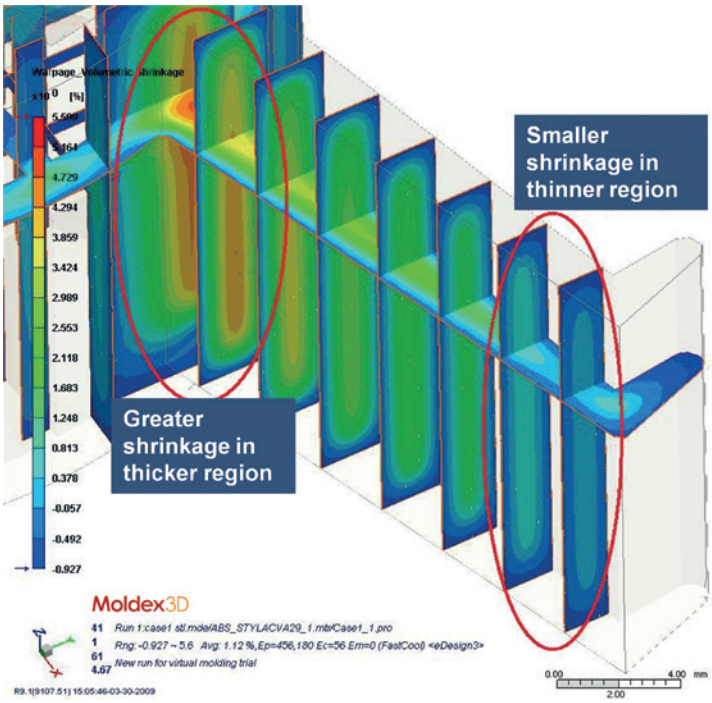


Figure 9.20 Shrinkage difference: thickness and geometry characteristics

4. Fiber Orientation Effects on Warp

As fiber orientation due to flowing creates anisotropic properties in the material, anisotropic shrinkage and warpage are thus generated. The fiber orientation effect can be verified by CAE. Fibers tend to align in the flow (forward) direction, especially in the area close to the mold wall. Shrinkage along the forward direction of fiber orientation is relatively smaller. If fibers are aligned well, the shrinkage along the long axis (forward) becomes smaller; if not, shrinkage would be similar in both directions. A randomized fiber orientation has a more uniform shrinkage along

and cross-flow direction compared to the aligned one with an anisotropic shrinkage, as shown in Figure 9.21.

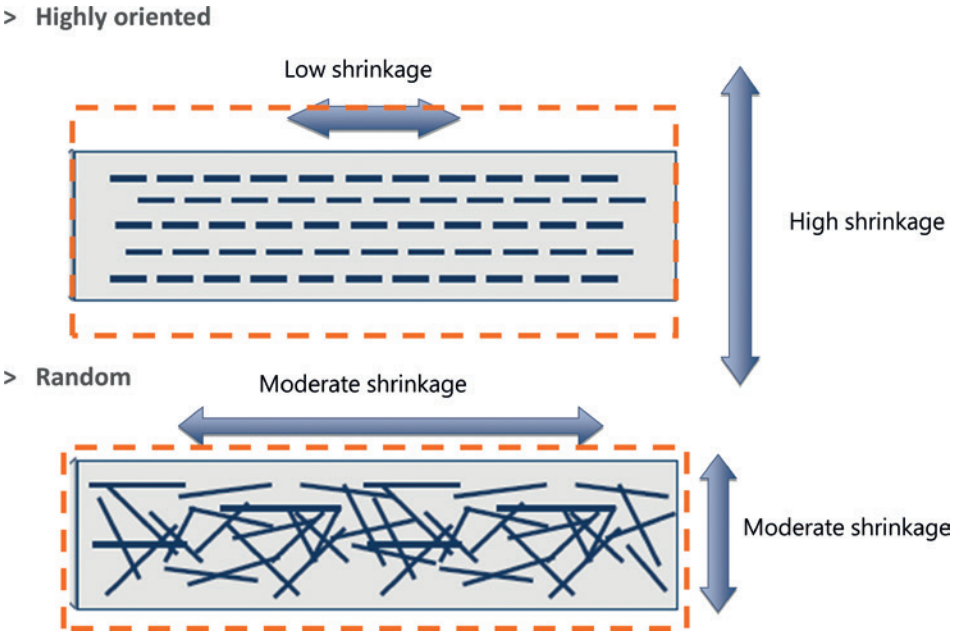


Figure 9.21 Highly-oriented and randomized fiber orientation, and corresponding shrinkage

Figure 9.22 shows a poor orientation of the fibers on the top half of the part, leading to isotropic shrinkage, but on the bottom part the fibers are highly oriented giving rise to strong anisotropic shrinkage. However, as the shrinkage along the direction of flow is smaller, we can see as a final result that the shrinkage on the bottom part is small, whereas that on the top half is large, causing the part to warp upward.

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