# Chapter 5 Deformation and Heat Transfer of Polymer Melt within the Mold Cavity during Injection Molding Process

# 1. Solidification of Polymer within the Mold Cavity

Polymer melt injected into the mold cavity solidifies due to heat transfer to the mold wall. The heat transfer starts immediately after the polymer melt at high temperature contacts to cold mold wall. Therefore solidification of the polymer melt takes place even in the filling stage, during which the polymer melt is flowing in the mold cavity. The heat transfer simultaneously occurring with the polymer flow affects the flow of polymer melt during the filling stage, and the melt behaves in somewhat unique manner.

In general, two-dimensional temperature profile in flow- and transverse-directions appears in a hot fluid flowing with a flow front through a narrow passage having cold walls. This temperature profile would be an intermediate one between the profiles for the following two extreme cases; (a) the case that thermal diffusion within the fluid is dominantly strong in transverse direction, and (b) the case that thermal diffusion in the transverse direction is quite limited. Under the former condition, temperature profile within the fluid is uniform in transverse direction, and changes only in the flowing direction as shown in Figure 5.1(a). To the contrary, under the latter condition, only the fluid adjacent to the walls is cooled, and steep temperature gradient appears mainly in the transverse direction as shown in Figure 5.1(b). Generally speaking, thermal diffusivity of polymeric materials is quite lower than those of other materials such as metals. In other words, Prandtl number of the polymer melt reaches up to  $10^5$ , and is quite larger than the other common fluids. Thus the temperature profile within the polymer melt injected into the mold cavity would be close to the one of the latter case.



Figure 5.1 Temperature distributions within a hot fluid flowing through a narrow passage having cold walls. Two extreme cases.

Figure 5.2 shows the behavior of polymer melt flowing in the mold cavity. One can observe in this figure that solidification layers (frozen layers) of polymer appears on both surface of the cavity wall due to heat transfer to the mold. This frozen layer gradually develops towards upstream of the polymer melt flow. This suggests that the melt flowing around the flow front due to fountain flow meets the cavity wall without cooling, and then cooled by the heat transfer to the mold wall. The cooling penetrates into the inner portion of the melt as the time elapsed, and thus the frozen layer develops to the opposite direction of the progress of flow front.

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Figure 5.2 Flowing behavior of polymer melt within the mold cavity during the filling stage.

Generation of frozen layers on the surface of polymer during the filling stage plays an important role for improving the productivity of injection molding process. Namely, the frozen layer generated on the surface of molded acts as a "shell" containing un-solidified polymer melt, and when this shell becomes strong enough for supporting the weight of molded itself or the force due to handling of the molded after the cooling stage, one can remove the product from the mold cavity before whole the polymer melt is entirely solidified.

# 2. Heat Transfer Dominating the Generation of Frozen Layer

Both of the accuracy of products and the productivity of injection molding process are strongly affected by the generation of frozen layer onto the polymer surface during the filling stage as mentioned previously. So it is important to understand the heat transfer phenomena dominating the frozen layer generation in detail for improving the injection molding processes.







Figure 5.4 Temperature distribution around the flow front region.

As shown in Figure 5.3, it can be considered that polymer melt moves on the flow front due to

fountain flow, meets the cavity wall without cooling, and then cooled by the heat transfer to the mold wall. If this is the case, and if the diffusion of heat within the polymer in the flowing direction is negligible as compared to that due to melt flow, heat transfer between the polymer melt and the cavity wall adjacent to the meeting point can be approximated as a transient heat transfer between two semi-infinite bodies. Namely, temperature profiles in the polymer and mold can be estimated by the following analytical solutions<sup>1)</sup> of the unsteady heat conduction between two semi-infinite bodies:

(a) in the polymer,

$$T_{p}(x,z) = T_{p0} - (T_{p0} - T_{i}) \operatorname{erfc}\left(\frac{z}{2\sqrt{\alpha_{p}t}}\right)$$

$$= T_{p0} - (T_{p0} - T_{i}) \operatorname{erfc}\left(\frac{z}{2\sqrt{\alpha_{p}x/u_{f}}}\right)$$
(5.1)

(b) in the mold wall,

$$T_{m}(x,z) = (T_{i} - T_{m0}) \operatorname{erfc}\left(\frac{-z}{2\sqrt{\alpha_{m}t}}\right) + T_{m0}$$

$$= (T_{i} - T_{m0}) \operatorname{erfc}\left(\frac{-z}{2\sqrt{\alpha_{m}x/u_{f}}}\right) + T_{m0}$$
(5.2)

where *x* and *z* are the coordinates measured from the melt-mold wall contact line as shown in Figure 5.4,  $u_{\rm f}$  the velocity of moving flow front,  $T_{\rm p0}$  and  $T_{\rm m0}$  the initial temperature of the polymer melt and mold wall,  $\alpha_{\rm p}$  and  $\alpha_{\rm m}$  the thermal diffusivities of the polymer and mold materials, respectively.  $T_{\rm i}$  appearing in Eqs. (5.1) and (5.2) shows the temperature at the interface between the polymer melt and mold wall, and can be estimated from the assumption of unsteady heat conduction between two semi-infinite bodies as follows:

$$T_{i} = \frac{\sqrt{\rho_{p}c_{p}k_{p}}T_{p0} + \sqrt{\rho_{m}c_{m}k_{m}}T_{m0}}{\sqrt{\rho_{p}c_{p}k_{p}} + \sqrt{\rho_{m}c_{m}k_{m}}}$$
(5.3)

where  $\rho$ , *c* and *k* are the density, specific heat and thermal conductivity, and the subscript *p* and *m* means the polymer and mold materials, respectively. Note that the interface temperature  $T_i$  is independent of the time *t* or distance *x* from the contact line, during the assumption of unsteady heat conduction between two semi-infinite bodies is valid<sup>\*</sup>.

$$\frac{d/2}{2\sqrt{\alpha_p t}} > 2 \tag{5.4}$$

or

$$Fo_p = \frac{\alpha_p t}{d^2} < \frac{1}{64} = 0.0156 \tag{5.5}$$

where is the thickness of polymer in the mold cavity. If is 5 mm, and if the polymer is polystyrene ( $\alpha_p = 1.15 \times 10^{-7}$  m<sup>2</sup>/s), the time t during which the assumption is valid is about 3.4 s. Generally speaking, since the filling stage of the injection molding process is completed within a few second, except for the molding of extremely large products such as the bumper of automobiles, the assumption of unsteady heat conduction between two semi-infinite bodies would be valid for entire period of the filling stage.

<sup>&</sup>lt;sup>\*</sup> Polymer melt in the mold cavity is generally thin, and thus cannot be treated as a semi-infinite body for heat conduction within it in general. However, during the changes of temperature due to heating/cooling on its both surfaces do not interact with each other, unsteady heat conduction occurring on both surfaces can be treated to be independent, and the unsteady heat conduction occurring on each surface is assumed to be that between the semi-infinite polymer slab and the semi-infinite mold wall. Namely, validity of the assumption is limited by the time when the temperature change due to heating/cooling on a surface reaches the middle of the polymer. Since value of the complementary error function *erfc* (2) at the variable of 2 is less than 0.005, the limitation can be estimated as follows:

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Let us imagine the actual phenomena with dimensional values. Assuming that the polymer injected into the mold cavity is polystyrene, which is a typical thermoplastic resin used as the material of daily necessities etc., density  $\rho_p$ , specific heat  $c_p$  and thermal conductivity  $k_p$  of the polymer are;

 $\rho_p = 1045 \text{ kg/m}^3$ ,  $c_p = 1320 \text{ J/(kg K)}$ ,  $k_p = 0.159 \text{ W/(m K)}$ . On the other hand, steel is often used as the material of mold wall, and thermal properties of steel are;

 $\rho_{\rm m} = 7860 \text{ kg/m}^3$ ,  $c_{\rm m} = 480 \text{ J/(kg K)}$ ,  $k_{\rm m} = 50 \text{ W/(m K)}$ . Initial temperature  $T_{\rm p0}$  of polymer melt is considered to be almost equal to the temperature of melt ejected from the heating barrel, and is about 230°C for polystyrene. Mold is usually cooled by passing the chilled water through it, and thus the initial temperature  $T_{\rm m0}$  is about 30°C. Under the condition, the interface temperature  $T_{\rm i}$  can be estimated from Eq. (5.3) as;

 $T_{\rm i} = 36.6^{\circ}{\rm C}.$ 

Since this interface temperature is quite lower than the solidification temperature  $T_s$  (glass-transition temperature  $T_g$ ) of the polymer, it is about 100°C for polystyrene, solidification of the melt takes place immediately after the melt meets the mold wall.

The shape  $\delta(x)$  of frozen layer can be estimated from the temperature profile within the polymer estimated by Eq. (5.1) as follows:

$$\delta(x) = 2 \sqrt{\alpha_p \frac{x}{u_f}} \operatorname{erfc}^{-1} \left( \frac{T_{p0} - T_s}{T_{p0} - T_i} \right)$$

$$= 2 \sqrt{\alpha_p \frac{x}{u_f}} \operatorname{erf}^{-1} \left( \frac{T_s - T_i}{T_{p0} - T_i} \right)$$
(5.6)

where  $T_s$  is the solidification temperature of polymer, and  $erfc^{-1}$  and  $erf^{-1}$  mean the inverse functions of the complementary error function and the error function, respectively. Because the interface temperature  $T_i$  is independent of the distance x from the flow front, frozen layer thickness increases in proportion to the square root of the distance x from the flow front as shown in Figure 5.4, and decreases inversely in proportion to the square root of the flow front velocity  $u_f$ .

As mentioned above, polymer melt is instantaneously cooled down to almost same temperature as the mold on its surface after the melt meets the mold wall. This is because that the product ( $\rho ck$ ) of density, specific heat and thermal conductivity of polymer is quite lower than that of mold material such as metals. Namely, high productivity of injection molding process, which is resulted from generation of frozen "shell" on the polymer surface during the filling stage, is based on the marvelous combination of thermal properties of the polymeric materials and the mold used for molding.

#### 3. Polymer Deformation Affected by the Frozen Layer Generation

As mentioned in the previous section, the interface between the polymer and mold cavity is covered with the frozen layer even in the filling stage. Therefore deformation on the interface is restricted by the existence of the frozen layer. On the other hand, polymer melt on the surface of flow front has no frozen layer, because heat transfer from the polymer melt to the gas (air) in the mold cavity is negligible. But on the surface of flow front, deformation of polymer to the prescribed shape never takes place, because the polymer in this region does not contact with the cavity wall, on which the prescribed shape is engraved. This means that, in the injection molding process, deformation of polymer to the prescribed shape mainly occurs only in the limited area adjacent to the "contact line" as shown in Figure 5.5.

In a literal sense, "frozen" material generated on the polymer surface would be rigid, and thus one may consider that forming of polymer surface cannot be performed even in the region adjacent

to the contact line. At the same time, it should be noted that the pressure of the polymer melt at the flow front is almost zero while the pressure at the mold gate is quite high since the pressure is consumed by the friction within the polymer melt due to flow, and that thus the forming force loaded on the material near the contact line is quite weak. Actually, however, transcription of the shape engraved onto the cavity surface occurs in the restricted region on the polymer-mold interface, although the interface is covered by the "frozen" polymer. This is because of the solidification characteristics of polymeric materials. Namely, different from the other industrial materials such as metals, stiffness of polymeric materials is gradually increases with lowering its temperature. So tip of the frozen layer, thickness of which is quite thin, can be formed by loading a forming force, even if the force is not so strong as to "break" the frozen layer. However, note that the forming on the polymer-mold interface is dominated by the "balance" between the stiffness of frozen layer and the forming force at the flow front region. If the injection pressure of polymer melt is lower than the appropriate range, and/or if the polymer is cooled excessively within the mold cavity, transcription of the shape engraved onto the mold cavity would not be completed and result in defects of moldings. Such a "tightrope walking" is inseparably combined with the high productivity of injection molding process.



Figure 5.5 Deformation ability of polymer on the interface between the polymer and mold wall.

In the practical production of injection-molded polymer products, engineers try to find out the "window" of the molding conditions under which the products of prescribed accuracy and functions can be produced with higher productivity as possible, and to control the molding process so as to maintain the molding conditions within the "window." However the process is sometimes performed under the condition out of the "window" due to fluctuation of surrounding conditions and/or accidental phenomena occurring around the injection molding process. In this case, accuracy/functions of the products may become unexpected ones. In order to avoid the generation of defects on the products, it is essential to enlarge the width of "window" of the molding conditions. Both the molding conditions under which the products can be produced in the prescribed accuracy/functions and the productivity of process are deeply related to the generation of frozen layer during filling stage of injection molding process as mentioned above. This point will be discussed in the next chapter by giving practical examples.

#### Problem

Suppose a practical melting processing, and research its temperature conditions, i.e. melt temperature before processing, solidification temperature of the material, initial temperature of mold, and thermal properties of the materials of the product and the mold. Then estimate the interface temperature between the melt and the mold by using Eq. (5.3), and discuss the cooling process of the material within the mold by comparing the result to the one of injection molding process of polymer.

# Reference

[1] Carslaw, H.S. and Jaeger, J.C.: Conduction of Heat in Solids (second edition), p. 88 (1959) Oxford at the Clarendon Press

# Chapter 6 Molding Defects Related to the Heat Transfer

## 1. Defects in Moldings

Molding defects are the phenomena by which the products cannot secure the prescribed shape and/or functions. Various phenomena are relating to the molding defects in general molding processing but the major factors in the defects in polymer processing are the following two phenomena:

(a) Rapid cooling of melt due to heat transfer to the metal mold wall.

(b) Volumetric shrinkage of the material due to solidification.

The defects related to the former phenomenon involve those generated due to increasing in deformation resistance of the frozen layer at the surface of the polymer melt as shown in the precious chapter. On the other hand, the defects related to the latter phenomenon are often observed not only in the polymer processing but also in the general melting processes; since the size and shape of the products are set up for the molten material, shrinkage of the formed melt directly results in inferior accuracy of the products.

Defects in polymer processing are sometimes originated by these phenomena separately, but in most of all cases, both of these phenomena simultaneously affect the quality of products. For example, the defects often observed in the practical polymer processing can be classified into the following groups from the viewpoint of the phenomena dominating the defect generation.

1.1 Defects related mainly to the phenomenon (a)

<u>1.1.1 Short-shot.</u> Short-shot is the phenomenon that the polymer melt flow within the mold cavity stops due to solidification before whole the cavity is filled by the melt, and thus molding of the products is not completed as shown in Figure 6.1. This defect is often observed in injection molding of the thin products, and in the practical molding process, the defect is usually avoided by increasing the injection velocity of polymer melt and/or by raising the mold temperature. A major factor of this defect is, as be easily supposed, the generation of frozen layer during the filling stage, i.e. rapid cooling of the melt due to heat transfer to the mold wall.



Figure 6.1 Short shot<sup>1)</sup>.

<u>1.1.2 Poor Transcription.</u> Transcribability of the minute shapes engraved onto the mold cavity surface is reduced by the deformation resistance of the surface layer of the polymer melt, which is solidified due to heat transfer to the mold wall during the filling stage, as shown in Figure 6.2. This defect affects the quality of products more significantly as the size of shapes transcribed onto the surface of products becomes smaller. For example, in the production of optical data disks, such as CD and DVD, poor transcription of the data pits, size of which is about 0.9-3.3  $\mu$ m in length, 0.5  $\mu$ m in width, and 100 nm in depth, results in a fatal error of the data recorded onto the disk, and thus is regarded as highly important. In the practical molding of the optical data disks, therefore, this defect is usually avoided by raising the mold temperature up to about 100°C and by applying a molding method so-called "injection-compression molding," in which the polymer melt is injected

into a cavity of the slightly opened mold halves, and then the polymer is compressed by closing the molds as shown in Figure 6.3.



<u>1.1.3 Weld-line</u>. Most of all the practical injection molded products often have "holes." These holes are formed by using a mold having inserts in the cavity. During the filling stage of the molding process of such a kind of products, flow front of the polymer melt is divided by the inserts, and then meets again at the downstream of the inserts. Since surface of the divided polymer melt is cooled due to heat transfer to the cavity wall or to the inserts, melt flow at the downstream of the inserts cannot return to the one at the upstream due to increase of deformation resistance. The change of melt flow results in a "trace" so-called "weld-line" as shown in Figure 6.4. Practical molded products having holes always involve weld-lines in the downstream region of the hole in varying degrees. Therefore the products the appearance of which has priority over the productivity are often painted in order to cover up the weld-lines. Moreover the mechanical strength around the weld-line is inferior to that of other region in general, and thus for producing polymer products loading stresses, construction and/or gate arrangement of the mold is devised so as not to generate weld-line as possible. This defect is also originated from the cooling of melt during the filling stage.



<u>1.1.4 Residual birefringence/residual molecular orientation.</u> Shear or elongation of polymer melt results in non-isotropic properties due to orientation of polymer molecules. In the filling stage of the injection molding process, flow of melt generates the molecular orientation. This molecular orientation relaxes quickly after the melt stops if the melt temperature is kept high. However if the melt is cooled and is solidified, the molecular orientation is also frozen into the polymer, and thus non-isotropic properties appears in the products. Among them, optical non-isotropy, including the one originated from the stress frozen in the polymer, is called as residual birefringence (see Figure 6.5). Since residual birefringence is a kind of optical deformation, residual birefringence itself or non-uniform distribution of it may be a fatal defect for the optical memory media or optical parts made through the polymer processing.



Figure 6.5 Residual birefringence<sup>2)</sup>.

### 1.2 Defects related to both phenomena (a) and (b)

The most typical defect related to both the rapid cooling of melt during the filling stage and the shrinkage of polymer due to solidification is so-called "flow-marks." On injection-molded polymer products, a "pattern," which seems to be related to the flowing behavior of polymer melt within the mold cavity, sometimes appears. This pattern is independent from the shape/texture of the cavity surface, and is called "flow-mark" in general. There are many kinds of flow-marks observed. Various phenomena are considered to dominate the generation of each flow-marks, and many researchers are now trying to find out the mechanisms of the flow-mark generation. Among them, generation mechanism of so-called "wave-like" flow mark (see Figure 6.6) has been reported<sup>1)</sup> so far. Namely, initiation of the wave-like flow mark is due to the warp of solidified layer in the region just after the flow front, and then the warped solidified layer is pushed to the cavity wall by the melt pressure and touches again the cavity wall. Repetition of these phenomena results in the "wavy" surface of the products as shown in Figure 6.6. The warp of solidified layer is dominated both by the cooling of polymer melt due to heat transfer to the mold wall and by the shrinkage of polymer due to solidification. This defect can be easily avoided by increasing the injection melt velocity and/or by raising the mold temperature, i.e. by reducing the generation speed of solidified layer on the melt surface. But in the practical molding of products having a complicated shape, this defect may appear in the region where the cross-section of mold cavity becomes wider, i.e. at which the melt velocity becomes slower.



Figure 6.6 Generation of wave-like flow mark<sup>3</sup>).

## 1.3 Defects related mainly to the phenomenon (b)

Many kinds of defects, e.g. sink-marks, warp, residual stress, and so on, appear on the injection molded polymer products are originated from shrinkage of the material due to

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solidification. In the melting process, molten material is fixed into a prescribed shape by a mold in general. So the shape and/or size of the solidified products do not coincide with those of the mold because of shrinkage of the material. One can easily deal with the problem originated from the shrinkage of materials if the products shrink similarly to the shape of mold cavity, but in actual the products shrink non-uniformly and thus deformations in the shape of products take place. Among them, the deformation that the surface of products is dented due to shrinkage of material (Figure 6.7) is called "sink-marks." When the overall shape of products deforms due to the shrinkage, it is called "warping" or "twisting" (see Figure 6.8). The reason why these deformations non-uniformly appear in a certain location is the non-uniform stiffness distribution of the solidifying molten material in the mold.



If the shrinkage of molten materials is restricted by the mold or the rigidity of the product itself, internal stress remains in the products. This "residual stress" can cause deformation of the products during its usage due to creep of the material. The residual stress results also in non-isotropy of the mechanical, optical and/or electric properties of the products.

These defects are unavoidable unless the materials whose specific volume does not change under the changing temperature, pressure, etc. are used both as the mold and the molding. It should be pointed out that, however, location, shape and/or distribution of these defects can be controlled by controlling the heat transfer during the cooling stage of the process, since they are dominated by the stiffness distribution of the solidifying material in the mold as mentioned above. 1.4 Defects originated from the other phenomena

Defects other than those described above, i.e. defects originated not from the rapid cooling of molten material during the filling stage nor from the shrinkage of molten materials due to solidification, may also appear on the injection-molded polymer products. For example, if gas produced in the polymer melt reaches at the surface of moldings during the filling stage, the gas bubble is elongated on the surface due to shear flow of the melt, and thus a trace of the gas bubble having rough surface appears on the surface of products. This defect is called "silver streaks." So-called "color-streaks," which is originated by uneven mixture of dye in the material, and "burn-marks," which is the mixture of degraded or burned polymer material generated by heating of melt due to shear heating or due to compression of gas within the mold cavity, are also the defects related not to the rapid cooling of molten material during the filling stage nor to the shrinkage of molten materials due to solidification. These defects are avoided in the practical injection molding process by using measures corresponding to the causes of each defects.

### 2. Heat Transfer Control for Avoiding the Defects Generation

As mentioned above, many kinds of defects observed on injection-molded polymer products are originated from the heat transfer between the polymer and the mold wall. Therefore generation of these defects can be controlled by controlling the heat transfer. For example, one can easily imagine that the residual birefringence originated from the shear flow of polymer melt during the filling stage is eliminated by reducing the cooling of polymer melt. Actual effect of this heat transfer control will be shown in Chapter 10 in detail. In the practical molding processes, however, such kind of heat transfer control is seldom applied. The reason is quite simple. The heat transfer control for avoiding the defects generation, i.e. reducing the cooling rate of polymer melt within the mold cavity, often results in elongation of process time and the productivity which is the most remarkable feature of the injection-molding process may be deteriorated as the results.

For example, if the mold temperature is raised so as to reduce heat transfer between the polymer melt and the mold wall during the filling stage, cooling of the polymer during the cooling stage is also reduced because the temperature of mold cannot be lowered so rapidly just after the filling stage is over due to its large heat capacity. In general the mold having high stiffness and durability is made of metals, and thus its heat capacity is quite larger than that of the polymer molded within it. Therefore the engineers' decision that the direct heat transfer control by controlling the mold temperature would not be applicable for the practical molding process is feasible from the thermal engineering point of view.

Fortunately, most of all the defects originated from the rapid cooling of polymer melt during filling stage can also be avoided by controlling the molding conditions other than those related to the heat transfer. For example, poor transcription mentioned in the section 1.1.2 can be easily improved by increasing the injection velocity even if the mold wall temperature is kept constant<sup>\*</sup>. So the engineers are groping for the measure for avoiding the defects generation so as to minimize the influence on the productivity. Such measures, or know-how, strongly depend on the "sense" of each engineers, and thus are not intuitively in general. In order to understand these measures, one should interpret them appropriately on the basis of knowledge on the injection-molding phenomena and heat transfer during the process. In the following chapters, therefore, practical injection-molding phenomena and the measuring techniques for them will be discussed.

#### Problem

Examine injection-molded polymer products close to you so as to detect molding defects remaining on them. And then predict the generation mechanisms of the defects.

#### References

- [1] Toshiba Machine Engineering Review, No. 20 (1998) p. 5
- [2] Kurosaki, Y., Satoh, I., Ishii, K.: Trans. JSME, ser. B, 56-522 (1990) pp. 504-511.
- [3] Tredoux, L., Satoh, I., Kurosaki, Y.: Polymer Eng. & Sci., Vol. 39, No. 11 (1999) pp. 2233-2241.

<sup>\*</sup> Essential mechanism of this improvement is also due to reduction of heat transfer during the filling stage. The mechanism will be discussed in Chapter 10 in detail by giving an instance.