Chapter 8 Modeling of Surface Deformation and Heat Transfer in the Polymer during Injection-Molding Process

1. Molding Defects Related to the Surface Deformation

Generation mechanism of molding defects appears on the injection-molded polymers has been discussed in Chapter 6. As mentioned in this chapter, the defects related to the deformation of polymer surface is originated from the shrinkage of polymer due to cooling/solidifying in the mold. For example, sink-marks take place when the polymer that shrinks as it is cooled and solidified in the core region, makes dents in the already solidified polymer in the surface region. Not only the polymer processing, the density of materials used in the melting processes is generally smaller in the molten state than in solid state. Therefore the melting processes, in which the prescribed shape is fixed onto the molten materials, inherently involve the surface deformation of the products. Since these deformations may be a fatal defect of the products, many types of countermeasures have been developed and applied in the practical melting processes. The most typical countermeasure is the method that the additional molten materials are poured into the mold so as to compensate the shrinkage of materials in the mold. This method is called as "packing-holding" in the injection-molding process of polymer, and as "riser" in the metal casting process. For thrusting the material into mold cavity, the pressure supplied from the plunger involved in the heating barrel, which is for injecting the polymer melt into the mold cavity, is applied in injection-molding of polymer and gravitational force acting on the material in the riser is applied in metal casting. These methods are effective to reduce the surface deformation of the products due to shrinkage on the whole. But one can easily suppose that residual stress/strain remaining in the products may increase with these measures, since the additional materials are thrust into partially solidified materials at a high pressure. And, if the materials in the mold cavity solidify too much, the additional materials cannot be thrust into the mold with the assumed pressure. Moreover whole the surface deformation is not totally eliminated by these countermeasures.

In order to devise root measures against the surface deformation of the products, it is needed to understand whole mechanisms dominating the generation of surface deformation. For example, indeed the sink-marks generate mainly due to the shrinkage of polymer in the core region of products, but the reason why the sink-marks appear on certain portions of the products' surface cannot be explained by the above mechanism only. In this chapter, therefore, mechanisms dominating the surface deformation of injection-molded polymer products are examined from the viewpoint of thermal engineering, and the models describing the defects generation are discussed.

2. Mechanism Dominating the Location of Sink-Mark Generation

In order to examine the mechanisms dominating the defects generation, one should understand whole the phenomena related to the defects generation. In this section, we pay attention to the sink-mark generation. The sink-marks are observed usually on the surface of products after the whole molding process. Then, at what timing do the sink-marks appear on the products' surface?

Figure 8.1 shows the timings at which the sink-marks appear and when the whole polymer in the mold cavity solidifies, measured by using a visualizing mold for various injection melt temperature. As shown in this figure, the sink-mark appears just before the whole polymer in the mold cavity solidifies. This suggests that, at the timing, core region of the polymer is still melted while solidified layer appears on the surface region like a "shell." Namely it is supposed that the sink-mark appears if the shell is deformed by the tensile force due to shrinkage of polymer melt in the core region, and that the stiffness of the shell dominates the location of sink-mark.



Figure 8.1 Timing of the sink-mark generation and solidification of whole polymer.

The stiffness of frozen layer developing on the surface region of polymer in the mold cavity is mainly depends on the thickness of it, which is determined by the heat transfer between the polymer and mold wall; polymer contacting with colder mold wall has a thick or stiff frozen layer, and vice versa. From this consideration, one can easily suppose that the sink-mark is localized in the surface region where the polymer is in contact with hotter mold wall than other region.

In order to confirm the feasibility of this hypothesis, location of sink-marks appear on a simple polymer strip was experimentally examined by using a mold the temperature of two opposite walls of which can be controlled independently¹⁾. Typical results of this examination are shown in Figure 8.2. As shown in this figure, when the temperatures of two opposite mold wall are different, almost all sink-marks appear on the product's surface that has been in contact with the hotter mold wall, while sink-marks appear on both surface if the temperatures of the two opposite mold wall are almost identical. This is because, as expected, the frozen layer developed on the polymer surface being in contact with the hotter mold wall is thinner or weaker than that developed on the opposite surface, and thus shrinkage of polymer melt in the core region makes dents mainly on the hotter surface.



Figure 8.2 Effect of mold wall temperature on the location of sink-marks.

During the examination, another phenomenon has been found. That is, when the temperature of the hotter wall is high enough, sink-marks appear only on the surface that has been in contact with the colder mold wall instead of the hotter surface. This means that the location of sink-marks is dominated not only by the stiffness balance of the frozen layer in the surface region of the products. 2/6

In order to search for the mechanism other than the stiffness balance of the frozen layer, sink-mark generation has been examined by changing the combination of temperature of the two opposite mold walls systematically. Polystyrene was used as the molding material. The results are summarized in Figures 8.3 and 8.4. As shown in these figures, sink-marks do not appear on the hotter surface if the temperature of hotter mold wall exceeds about 100°C. This temperature corresponds to the glass-transition temperature of polystyrene, and above the temperature, the material does not solidify. Nevertheless sink-marks do not appear on the hotter surface. This is because the adhesion force between the polymer and mold wall becomes strong enough to support shrinking polymer in the core region. It is known² that, in general, the adhesion force between a material and a solid surface depends on the interface temperature between them, and becomes markedly strong when the interface temperature exceeds the softening point of the material because the material can fit closely to the solid surface having surface roughness.







Figure 8.4 Schematic diagram showing the location of sink-marks against the mold wall temperatures.

From these results, it can be concluded that sink-marks are originated by the shrinkage of polymer in the core region of the product, but that the location of the sink-marks is dominated by both the stiffness distribution of the frozen layer developing on the surface region of the product and the adhesion of polymer to the mold wall³. This concept or model is effective for the sink-mark generation on injection-molded polymer products of various shapes and functions, and therefore is applied for controlling the location of sink-mark generation in the practical molding processes.

3. Mechanism Dominating the Wave-Like Flow-Mark Generation

Another typical defect related to the deformation of products' surface is so-called flow-mark. Flow-mark is the generic terms of the defects those the traces seem to relate to the flow pattern of the polymer melt during the filling stage appear on the surface of products. Among them, generation mechanism of the wave-like flow-mark, which is the defect that many grooves appear on the product's surface in spite of the shape of the mold wall as shown in Figure 6.6 (Chapter 6), has

been experimentally examined⁴⁾ in my lab from the thermal engineering point of view.



Figure 8.5 Development and warp deformation of frozen layer just behind the flow front.

Visualized results of the flow-mark generation showed that the wave-like deformation of the surface region of polymer starts at the contact point between the polymer melt and the mold wall just behind the flow front during the filling stage. This suggests that development of the frozen layer just behind the flow front can cause the flow-mark generation. In order to make the frozen layer deform in a wave-like shape, it is essential that a bending force for separating the polymer surface from the mold wall is generated in the developing frozen layer, since the surface layer of the polymer is continuously pressed onto the mold wall due to the injection pressure. As the bending force, I supposed the force due to warp deformation of the frozen layer. Figure 8.5 shows the concept of this warp deformation of frozen layer. When one observes the development of frozen layer just behind the flow front from a point fixed on the mold wall, thickness of the frozen layer at a certain point increases as the flow front moves forward. Since the newly solidified polymer on the frozen layer shrinks due to the solidification, the frozen layer tends to warp so that the outer surface of it becomes convex. The change of curvature dC of this warp deformation at the position x during an finite time dt can be estimated theoretically from the theoretical solution of temperature distribution in the frozen layer, Eq. (5.1) in Chapter 5, as follows:

$$dC^{*} = \alpha \left(T_{s} - T_{i}\right) \frac{1}{2} \frac{dt^{*}}{x^{*}} / \delta^{*}(x^{*}) = \frac{\alpha \left(T_{s} - T_{i}\right) \frac{1}{2}}{erf^{-1} \left(\frac{T_{s} - T_{i}}{T_{i0} - T_{i}}\right) 2/Fo} x^{*-\frac{3}{2}} dt^{*}$$
(8.1)

where T_s and T_i the solidification temperature of the polymer and the interface temperature between the polymer and mold wall, α the expansion coefficient of the polymer in solid state, respectively, and erf^1 shows the inverse function of error function. In this equation, curvature *C*, position *x* and time *t* were shown in dimensionless forms, marked with *, by using the wavelength λ of the flow-mark and the time determined by the flow-mark wavelength and the flow front velocity, λ/w_m , as a characteristic length and a characteristic time. Moreover, *Fo* is the Fourier number defined as

$$Fo = \frac{k_p}{\rho_p c_p} \frac{1}{w_m \lambda}$$
(8.2)

Paying attention to that the location x^* can be replaced by the time t^* , the curvature *C* of a hill of the flow-mark is estimated by integrating the curvature change *dC* of the frozen layer during the period in which a hill of the flow-mark generates, i.e. $t^* = t^*_c$ to 1.

$$C^{*} = \int_{t_{c}^{*}}^{1} dC^{*} = \frac{\alpha (T_{s} - T_{i})}{erf^{-1} \left(\frac{T_{s} - T_{i}}{T_{r0} - T_{i}}\right) 2\sqrt{Fo}} \left(\frac{1}{\sqrt{t_{c}^{*}}} - 1\right)$$

(8.3)

where t_c (or t^*_c) is the time at which the flow-mark starts to generate, and is corresponds to the time when the warp force due to development of the frozen layer becomes strong enough for "removing" the frozen layer from the mold wall.

Figure 8.6 shows the comparisons between the dimensionless curvatures, which can be evaluated as the ratio of the depth to the wavelength of flow-mark, of flow-marks reported in literatures and those estimated from Eq. (8.3). As shown in this figure, Eq. (8.3) estimates the shape of flow-marks very well regardless of the materials of the products and mold as well as the molding conditions. This supports the hypothesis that the wave-like flow-marks are originated by the warp deformation of the frozen layer developing just behind the flow front of polymer. Moreover, Eq. (8.3) suggests that the curvature of flow-mark decreases with increasing the temperature difference $(T_{p0} - T_i)$ between the injected melt and the polymer-mold interface, and with increasing the injection velocity w_m . In the practical molding process, engineers often increase the temperature and/or velocity of polymer melt injected into the mold cavity in order to avoid the generation of wave-like flow-marks. This practical measure agrees well with the one suggested by Eq. (8.3).



Figure 8.6 Comparisons between the dimensionless curvatures of actual flow-marks and those estimated with Eq. (8.3).

As described above, most of all the defects related to deformation of the products' surface can be modeled by using the mechanisms related to the generation of frozen layers in the surface region of polymer. In order to control the generation of these defects, therefore, it would be most effective to control the development of the frozen layer, i.e. heat transfer between the polymer and the mold wall. In fact there have been many measures for avoiding the defects by controlling the heat transfer so far. However the heat transfer control often results in the reduction of productivity, and thus the heat transfer control that little affect the productivity is keenly required in the practical molding. Ideas for the heat transfer control will be discussed in the next chapter.

Problem

As mentioned in the section 2, behavior of the injection-molded polymer within the mold cavity is affected by the adhesion force between the polymer and the mold wall, which depends strongly on the interface temperature between them. Search a case in which the adhesion force is positively utilized other than the injection-molded polymer, and discuss the effect of temperature on its effectiveness.

References

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