Chapter 7
Evaluation of Injection-Molding Phenomena
Part 1: Measurement of temperature distribution in the molded materials

1. Evaluation of Injection-Molding Phenomena

It is effective to evaluate the phenomena occurring in the materials during the injection molding process for avoiding the generation of molding defects mentioned in the previous chapter, and for improving the productivity of the injection molding process itself. But in general it is quite difficult to observe the behavior of polymer materials directly during the molding process, since the molding phenomena take place within the cavity of mold that is made of metals. In this chapter, therefore, measuring methods for the injection molding phenomena occurring in the mold cavity and their results are discussed so as to obtain the basic understanding for improving the injection molding process.

In order to examine the phenomena occurring in the melting processes from the thermal engineering point of view, it is important to know the flowing or deformation behavior of the molten material and temperature distribution within it during the forming process. In this part, as the first step, measurement of temperature distribution in the molded materials and the results are discussed.

2. Measurement of Temperature Distribution of the Injection-Molded Polymer within the Mold Cavity

Since temperature dominates viscosity or rigidity of the materials, measurement of the temperature of materials has great meaning for examining the phenomena occurring during the molding processes. Temperature of materials is one of the most common measuring variables in the field of engineering, especially in thermal engineering, and therefore many kinds of techniques are applied for measuring the temperature. It should be noted that, however, temperature measurement in the melting processes requires higher accuracy than that in the ordinary heat transfer applications. This is because, in the melting process, engineers require the material temperature itself that dominates deformation behavior of the material, while temperature difference dominating heat transfer between two points is more important in the ordinary heat transfer applications. Most of all the methods of temperature measurement have been developed for the heat transfer applications, and thus a certain attention should be paid for applying the measuring methods for temperature measurement in the melting processes. In the following, examples of the temperature measurement of injection-molded polymer materials within the mold cavity are shown so as to discuss the feature of these measuring methods and the heat transfer phenomena occurring in the injection-molded polymers.

<u>2.1 Direct measurement by using thermometers</u>

In order to measure directly the polymer temperature during injection-molding process, thermometers should be inserted into the mold cavity. Moreover, in order to examine the solidification of molten polymer, minute temperature distribution within the polymer should be measured since steep temperature distributions often take place within the polymer due to its low thermal conductivity or high Prandtl number.

For the measurement of local temperature within a medium, thermocouples are often utilized in general. This is because the local temperature can be measured by thermocouples with high spatial resolution. Measuring point of a thermocouple is strictly limited at the junction of two kinds of metals, and the sensitivity is not affected by the size of the junction. Due to this feature of thermocouples, fine wires of metals can be used for fabricating the thermocouples, and thus it is easy to install the thermocouples into a mold having a closed cavity space. For measuring the temperature distribution within the polymer materials during molding process by using a large number of thermocouples, however, one may have difficulty in supporting thermocouples at the prescribed positions. This is because polymer melt flowing in the mold cavity is highly viscid in general, and because the thermocouples are confined in the molded polymer after the whole molding process is over and thus the thermocouples cannot be reused. Therefore, in order to apply thermocouples for measuring the temperature distribution within the polymer during the molding process, it is required to develop an inexpensive measure for supporting the thermocouples at high rigidity.

One of the solutions of this problem is the use of "integrated thermocouples sensor[1] (ITS)," which is a sensor having a group of thermocouples made by spattering of metals onto a film-like substrate of a heat-resistant polymer such as polyimide. Figure 7.1 shows a typical ITS. This ITS has 15 Cu-Ni thermocouples fabricated on a polyimide film of 0.1 mm thick at an intervals of 0.3 mm. This type of sensor can be mass-produced, and thus may be thrown away after a cycle of molding process.

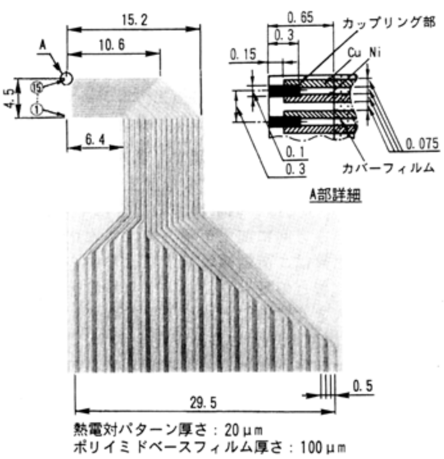


Figure 7.1 Integrated thermocouples sensor[1].

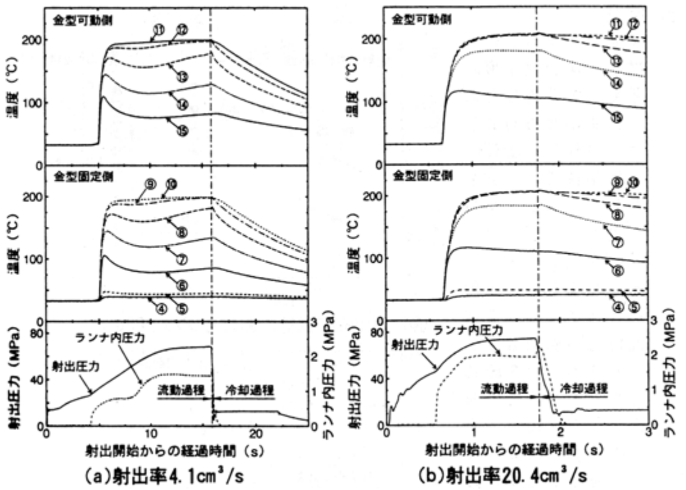


Figure 7.2 Temperature responses of injection-molded polymers measured by ITS[1].

Figure 7.2 shows typical temperature change of polymer and mold during the injection-molding process measured by using the ITS. In the measurement, polystyrene melt at the temperature of 200°C was injected into a mold at about 31°C. Thermocouples #6 through #15 were located in the polymer, and #4 and #5 were in the mold wall. As shown in these results, temperature of the polymer melt adjacent to the mold wall drops sharply just after the melt is injected into the mold, while the polymer at the center portion (thermocouples #10 and #11) is kept nearly at the constant temperature, which is almost equal to the injection melt temperature (200°C), throughout the molding process. On the contrary, mold wall temperature rises during the molding process due to heat transfer from the hot polymer melt, but the temperature change is quite smaller than that in the polymer. These can be explained by the fact that the product of density, specific heat and thermal conductivity of polymer materials is quite smaller than that of metals as mentioned in Chapter 5.

Careful inspection of Figure 7.2 shows that, especially in the case of low melt injection rate, polymer temperature in the intermediate region between cavity wall and center portion decreases at first and then rises again in the latter molding process. This is due to the melt flow generated by the packing-holding pressure. In the practical injection-molding process, polymer melt is often pressed into the mold cavity even after the melt fills whole the cavity so as to reduce the generation of sink-marks and/or warpage of the products. This process is so called packing-holding process, and the pressure applied to the melt during this process is called as the packing-holding pressure. By the packing-holding pressure, new polymer melt, i.e. high temperature polymer melt, is poured into the mold cavity so as to compensate the shrinkage of polymer filled in the mold cavity due to solidification, and thus the polymer in the mold cavity is heated again by the hot melt newly incoming into the center portion of the polymer.

2.2 Remote measurement from the outside of the mold cavity

Direct measurement of temperature by using thermometers inserted into the medium is indeed quite intuitive and highly accurate measurement can be done by the thermometers if installing and calibration of the thermometers were performed properly. However, since the thermometer basically measures temperature of medium at a point, more than one thermometer must be installed into the medium, or a thermometer traversing in the medium must be used for measuring the "distribution" of temperature. It is not only troublesome but also the cause of measurement error due to the existing/traversing the thermometer within the medium.

In order to avoid the problem related to the use of thermometer, an infrared thermography is applied for measuring the temperature distribution. The infrared thermography measures the intensity of infrared radiation from the medium, and converts the intensity to temperature. Since the infrared radiation emitted from the medium is a kind of light, 2-dimensional temperature distribution can be obtained remotely by the thermography with an optical system like an ordinary camera. The thermo-camera has been often applied for the temperature measurement in the field of thermal engineering, but nowadays is tried to apply for temperature measurement in the polymer processing.

In order to apply the thermo-camera for measuring temperature of polymer in the molding process, some devices and considerations are required. First of them is the use of special mold for "visualizing" the temperature distribution of polymer in the mold cavity. As mentioned above, thermo-camera measures infrared radiation emitted from the medium. So if one wants to measure the temperature of polymer within the mold cavity, a "window" should be installed on the mold wall so as to guide the radiation to outside of the mold cavity. Since most of all the thermo-camera systems on the market sense the infrared radiation of wavelength range from 3 to 5 μm or from 8 to 13 μm, the window must be made of the materials transparent for the infrared light. Inorganic crystals such as Calcium Fluoride (CaF_2) and/or Zinc Selenide (ZnSe) are often used as the materials of the window. It should be noted that these materials are generally brittle, and thus are hardly machined in a complicated shape. Figure 7.3 shows an example of the test mold for "visualizing" the temperature distribution of the molded polymer, which is having a window made of CaF_2 for temperature measurement and another window made of acrylic resin for visualization of flowing behavior of the polymer melt.

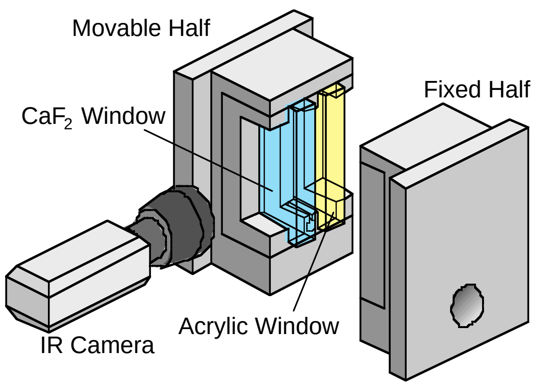


Figure 7.3 A test mold having windows for temperature measurement and flow visualization.

Another matter to be attended to for applying thermography for temperature measurement of polymer in the molding process is that some polymers are semi-transparent for the infrared light sensed by thermo-camera systems. In general, thermo-camera systems display the temperature distribution by assuming that the incident radiation comes from the "surface" of the objective material. This is because most of all the industrial materials such as metals and/or ceramics are opaque for the radiation. However, radiation emitted by some kinds of polymer material is not only from its surface but also from the inner portion as shown in Figure 7.4 because the polymer is semi-transparent for the radiation, and thus the temperature distribution measured by thermography may be affected by the temperature of inner part of the polymer. Note that steep temperature distribution tends to take place in the polymer material because of its low thermal diffusivity. Therefore one should be careful with interpretation on the temperature distribution of polymer measured by using thermo-camera.

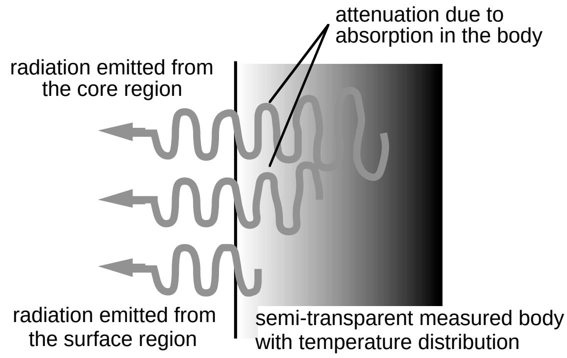


Figure 7.4 Emission of radiation from a semi-transparent material.

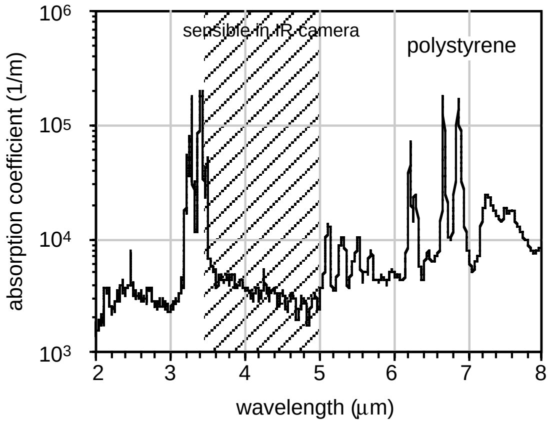


Figure 7.5 Spectrum of absorption coefficient of light: polystyrene

Figure 7.5 shows the spectrum of light absorption coefficient of polystyrene in infrared region. As shown in this figure, absorption coefficient in the wavelength range from 3.5 to 5 μm, which can be sensed by the thermo-camera system used in my lab, is about 3000 1/m. This means that the thremography measures the radiation emitted from the region from the surface to the inner part of the depth at about 1/3000 m = 0.3 mm. Namely the measured temperature is the average of that in this region. In order to measure the real surface temperature of polymer by using thermography, an optical filter that transfers the infrared light only in the wavelength range in which the polymer is highly opaque is sometimes installed onto the thermo-camera. However this countermeasure is not always recommendable because sensitivity of the thermo-camera is reduced by the filter and thus the S/N ratio of the temperature image obtained drops. Rather than that, it is more effective to increase the absorption coefficient of polymer in the wavelength range sensed by the thermo-camera by mixing a small amount of pigments, e.g. carbon black.

Figures 7.6 and 7.7 show the temperature images of polymers obtained by using a thermo-camera under the injection-molding process. Figure 7.6 is the temperature of the polymer melt flowing in the mold cavity, and Figure 7.7 is the temperature around the weld-line generated in the region behind a pin inserted in the mold cavity[2)]. As shown in these figures, one can easily measure or visualize the temperature distribution of polymer under the molding process by using thermography, but it should be noted that the accuracy of measured temperature is limited to several K; temperature resolution of thermo-camera is about 0.1 K in general, but due to the measuring principle accurate evaluation of absolute temperature is quite difficult. Moreover, temperature distributions shown in these figures are not necessarily those at the polymer surface because of semi-transparency of the polymer as mentioned above. For example, in Figure 7.6, temperature in the contact region just behind the flow front is observed higher than that in the upstream region. This is because, in the region just behind the flow front, thickness of the polymer cooled by the mold wall (window) is quite thin, and thus high temperature polymer in the core region is considered to be seen through the cold polymer at the surface.

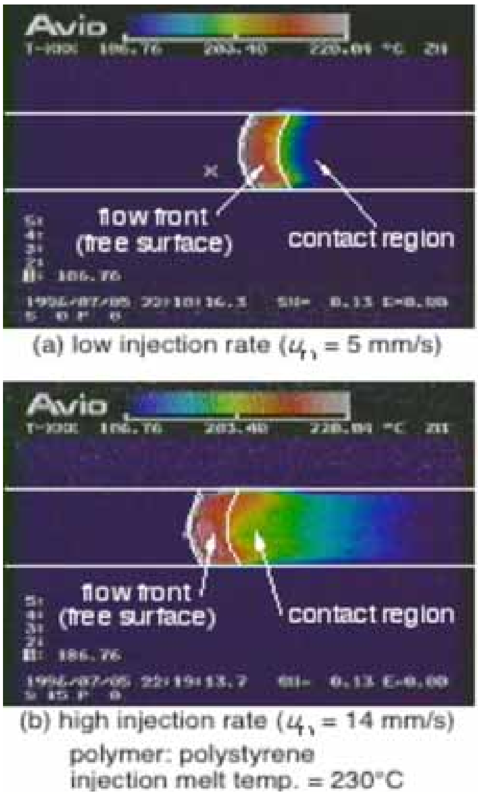


Figure 7.6 Temperature distribution of polymer around the flow-front.

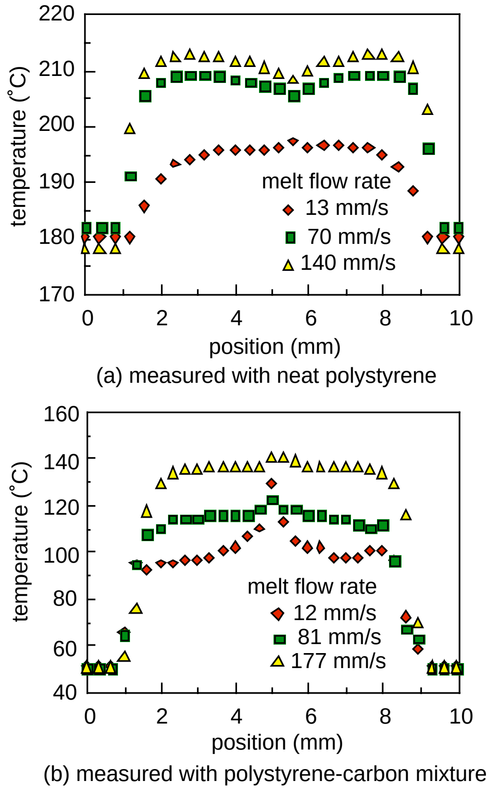
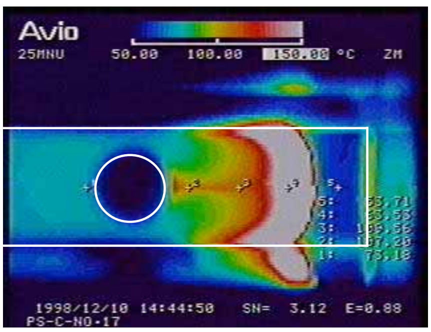


Figure 7.8 Span-wise temperature distribution across the weld-line[2].



flow front velocity = 12 mm/s
injection melt temp. = 220°C
polystyrene with carbon powder

Figure 7.7 Temperature distribution of around the weld-line[2].

As mentioned above, polymer temperature measured by thermography is affected by the transmissivity of polymer. Figure 7.8 shows the transverse temperature distributions across the weld-line measured by using thermo-camera (Figure 7.7); Figure 7.8(a) shows the temperature distributions for neat polymer, and Figure 7.8(b) is those for the polymer mixed with 1 wt% carbon black powder. Comparing these two graphs, one can understand that the temperature at the weld-line is lower than that in the other regions for neat polymer, while that the weld-line temperature is higher for the carbon-mixed polymer on the contrary. This can be explained by the facts that, at the weld-line, there is a small groove so-called V-notch, and thus the surface is not in contact with the mold wall (window). Therefore polymer temperature at the real surface of the weld-line is higher than that of other regions. On the other hand, polymer in the core region at the weld-line is cooled due to heat transfer to the pin, and thus the lower temperature is measured if the polymer in the core region is seen through the polymer at the surface. This result suggests that, paradoxically speaking, thermography can be applied for obtaining 3-dimensional temperature measurements of polymer, if the measured data is appropriately interpreted according to the characteristics of polymer for infrared radiation transfer.

3. Heat Transfer Phenomena Occurring in Injection-Molded Polymer Deduced from the Measured Temperature Distribution

Temperature distributions within the injection-molded polymer obtained through both the direct- and remote-measurements mentioned above show that the surface region of the polymer cooled due to heat transfer to the cold mold wall quite rapidly, but that temperature of the core region is not readily affected by the heat transfer because of the low thermal diffusivity of polymer materials. It was also shown that the polymer on the flow-front surface is kept at high temperature during the filling stage, since un-cooled polymer melt is continuously supplied on the flow-front region due to so-called fountain flow. Namely, it can be concluded that the model of heat transfer between the injection-molded polymer and mold wall, which was described in Chapter 5, is feasible both quantitatively and qualitatively. Heat transfer within the polymer is however affected also by the flowing/deformation behavior of polymer melt during the molding process. Therefore, details of the heat transfer will be discussed in the next chapter together with the measurement of flowing and deformation behavior of polymer during the molding process.

Problem

Suppose that the surface temperature of a material is measured by using a thermo-camera. The material is initially at a uniform temperature T_0, and the surface is suddenly heated at the constant temperature T_1 from the time t = 0. Derive the error of the measured surface temperature as a function of time, assuming that the temperature distribution within the material in depth-direction can be estimated by using an analytical solution of unsteady heat conduction in a semi-infinite solid

$$T(z,t) = (T_1 - T_0)\, erfc\left(\frac{z}{2\sqrt{\alpha\, t}}\right) + T_0 \tag{7.1}$$

and that thermography measures mean temperature of the object in the region of the depth about $1/\beta$, where α is the thermal diffusivity and β is the absorption coefficient of the material. Note that the integral of complementary error function is derived as follows:

$$\int_0^{\delta} erfc\,\xi\, d\xi = \frac{1}{\sqrt{\pi}}\left(1 - e^{-\delta^2}\right) + \delta\, erfc\,\delta \tag{7.2}$$

References

[1] Murata, Y., Abe, S. and Yokoi, H.: Seikei-Kakou'97 (Proc. Annual Meeting of the JSPP '97), (1997) pp. 45-48.

[2] Saito, T., Satoh, I., Uesugi, K. and Handa, K.: Seikei-Kakou, 12-6 (2000) pp. 325-331.