Chapter 3
Polymer Processing: Melting Processing for "Plastics"

1. What is the "Plastic?"

The definition of the "plastic" is "the material, which contains high-polymer as the essential part, and which is formable into other shape by utilizing its flow in a certain part of the processing (JIS-K6900-1994)." From the definition, therefore, the word "plastic" means a kind of material, but in general, it also means the products made of plastic material.

The most of plastic material we use in our daily life is the material synthesized from petroleum, coal and so on, and is called as "synthetic resin." Of course some plastic materials, such as pain resin or natural rubber, are the natural-made resin, but nowadays one is able to consider that the word "plastic" means a synthetic resin.

Synthetic resin has a history of only 150 years. In 1868, production of "Celluloid," which is a thermoplastic material made of camphor and nitro-cellulose (both of them are natural/semi-natural materials), has been industrialized. "Bakelite," which is made from phenol resin (first synthetic resin invented in 1872), has been on the market in 1909. Most of all the plastics we are using today, such as acrylic resin, poly-vinyl chloride, polystyrene, polyamide, polyethylene, and so on, were developed before and after the WW II (1939-1945). So the plastics are one of the newest material used for industrial purposes.

The plastic materials can roughly be divided into two groups, thermoplastic resin and thermoset resin, from their behavior during the processing.

1.1 Thermoplastic resins:

Thermoplastic resin is the material that can be melted by heating the solid and be solidified by cooling the melt. Melting due to heating and solidification due to cooling are reversible, and the material solidified from the melt can be melted again by heating.

The thermoplastic resin materials, such as polystyrene, polyethylene and acrylic resin, are used as the materials of the daily necessities, the case of electric equipment, the polymer parts of automobiles, etc. This is because, as mentioned in the next section, the thermoplastic resin can be molded by using relatively simple facilities with high productivity.

1.2 Thermoset resins:

Thermoset resin is the material that can be solidified by polymerization of low-polymer raw material, which is usually supplied as a liquid, triggered by heating, irradiation of light, or adding curing agents. The most typical thermoset resins are the phenol resin that is used for making Bakelite and Epoxy resin that is often used as an adhesive. Solidified thermoset resins cannot be melted by heating again; heating of solidified thermoset resins results in decomposition/degradation of the materials. Since polymerization of the thremoset resin is usually a chemical reaction with heat generation, cooling of the material may needed to control the curing process.

Thermoset resins are not so often used for making the daily necessities because of its difficulties in molding, but are used as a matrix of composite materials combined with high-strength materials such as glass- or carbon-fibers, so as to utilize their thermal resistance and high specific strength. Circuit boards for electronic equipment and chassis of aircraft/racing cars are the typical examples of the composite materials.

2. Processing of the Thermoplastic Resins

Whether the resin is thermoplastic or thermoset, heating/cooling are necessary during the processing of the plastic materials. In the processing of thermoplastic resins, particularly, making the molten material requires heating and solidification of formed products requires cooling the material as well. At the same time, products made of thermoplastic resins are common in our daily life, and thus the functions required for the products are quite broad. In the following, therefore, I will mainly discuss the processing of thermoplastic resins.

There are many kinds of methods for processing thermoplastic resins, and most of these have been utilized for production of actual products. The processing methods in practical use are classified as follows according to the shape and functions of the products.

2.1 Drawing and extrusion (Figure 3.1)

Long products having an uniform cross section, such as pipes, wires and L-shaped rods, are usually made through the process called "drawing" or "extrusion." In these processes, molten material is drawn or extruded through a "die" which has the mouse having the same shape as the cross section of the product, and then the material is cooled down so as to fix the shape of product. In general, since cooling at the die is not enough to solidify whole the material, the material pass through the die is cooled by passing it under a water pool or by using a water spray.

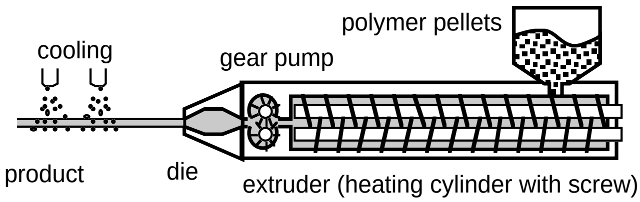

Figure 3.1 Extrusion.

2.2 Injection molding (Figure 3.2)

Injection molding is the process that the molten material is injected into a mold cavity, the shape of which is almost the same as the final product, and is cooled down so as to fix the shape of the material. This molding process has flexibility for the shape of products, and thus the injection molding process is commonly used for manufacturing the wide-range of plastic products, from the daily necessities having relatively simple shape to the products having complicated shape, such as the cases and containers of electronic equipment. In this process, since the polymer melt viscosity of which is quite large is injected into a mold cavity at high flow rate, injection pressure becomes quite high, e.g. upto several hundreds MPa, and thus large cramping force of the mold halves is required for molding large products. In addition to this, by this process, limited number of products can be obtained through one shot of the molding. This means that the process should be speeded up if one wants to produce the products at high productivity.

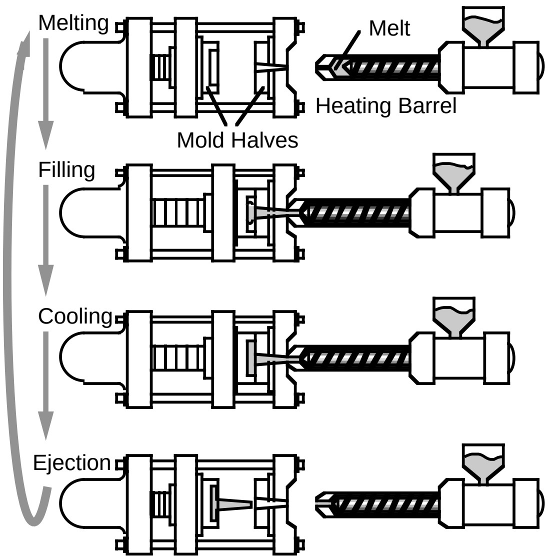

Figure 3.2 Injection molding.

2.3 Vacuum forming and hot-press forming (Figure 3.3)

In these processes, polymer material preformed like a board or film is softened by heating first, put it on the mold, and then is pushed against a mold by using a vacuum pressure (vacuum forming) or an opponent mold (hot-press forming). These processes require less forming force, and simpler mold than that of injection molding can be used. But the preciseness of products is generally inferior to the injection molding. Accordingly the vacuum forming and/or hot-press forming are usually applied for producing simple-shaped products, such as tray of foods.

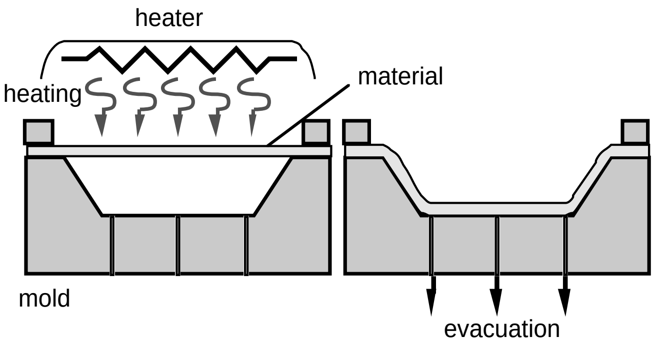

Figure 3.3 Vacuum forming.

2.4 Blow molding (Figure 3.4)

Blow molding is the process often used to produce hollow products such as bottles. Molten polymer is extruded as a cylindrical shape first (this material is called as "parison"), the material is clamped between a pair of female molds, and then is pushed against the mold by the pressure of gas blown into the cavity of the material. The strongest point of this process is the ability to produce hollow products. Nowadays, therefore this process is applied also for producing functional parts, such as air-spoilers of automobiles.

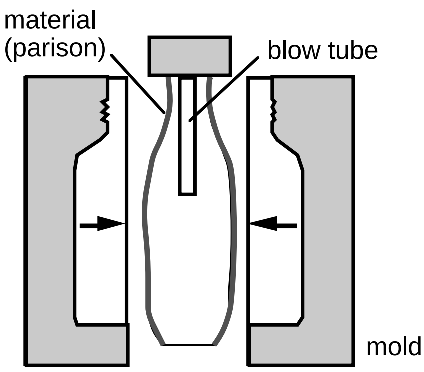

Figure 3.4 Blow molding.

2.5 Film forming (Figure 3.5)

Plastic films are usually formed by stretching the molten polymer extruded in a plate-like shape. The stretching the polymer material is not only for making the material thinner, but also for developing orientation of polymer molecules; molecular orientation results in strengthening in tensile strength of film in the direction of orientation. In the practical film forming process, stretching of the material is achieved by using tenters or rollers, or by using pressure of air blown into the cylindrical polymer material (inflation film forming).

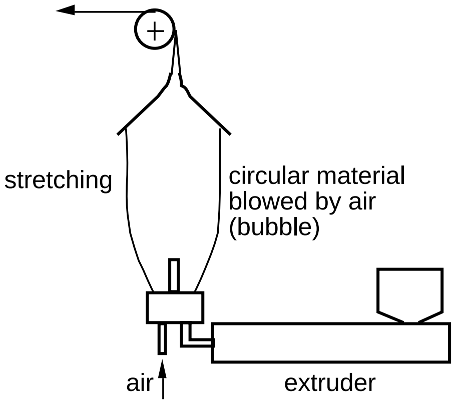

Figure 3.5 Inflation film forming.

2.6 Fiber drawing (Figure 3.6)

Most of all the synthetic fibers (mono-filament) are made by stretching the molten polymer extruded as a thin rod. Note that generally used strings are made by twisting some mono-filaments together. Stretched materials become stronger in the stretching direction due to molecular orientation. Cross section of the rod before stretching is chosen according to the functions intended the fiber to acquire.

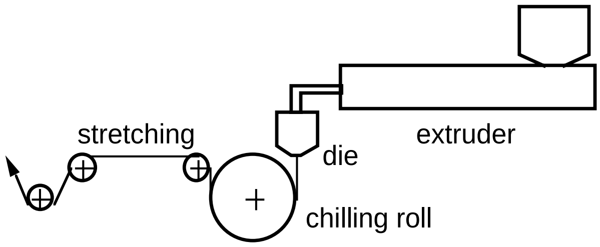

Figure 3.6 Fiber drawing.

2.7 Others

There are many processes for polymer processing other than those described above, and they are used in manufacturing of practical polymer products. For example, skin of the dashboard of automobiles having a leather-like texture is often made with a soft polymeric material. In order to form such skins, "power-slush forming" is applied. In this method, powder of soft material is scattered over the inner surface of heated female mold, molten and stuck material onto the mold is cooled, and then removed from the mold as the product. Anyway in all the processes, the materials are commonly melted by heating first, formed by adding some forces, and then solidified by cooling so as to fix the shape and functions of the products.

3. Injection Molding of Polymeric Materials

Most of all the plastic products made of thermoplastic resins are manufactured by the injection molding process. This is because of the flexibility on the shape of products as mentioned previously.

As shown in Figure 3.2, the injection molding process consists of the following four successive stages.

(1) Melting stage: Raw polymeric material supplied in a form of pellets or powders is melted in a heating barrel. Molten polymer is accumulated in the front part of the heating barrel.

(2) Filling stage: Molten polymer accumulated in the front part of the heating barrel is injected into a mold cavity at high flow rate. The molten polymer flows in the mold cavity and is formed in a shape of final product.

(3) Cooling stage: Molten polymer filled in the mold cavity is cooled by the heat transfer to the mold, and solidified within the mold cavity.

(4) Demolding stage: Solidified polymer, i.e. final product, is removed from the mold cavity by opening the mold halves.

These four successive stages are repeatedly performed so as to obtain the products continuously.

The melting stage is mostly common in the processing of thermoplastic resins, and thus the processing machines including the injection molding machine usually have a heating barrel which contains a screw for mixing, kneading and driving the polymer material. During the melting process, mixing the polymer in the heating barrel is required because of thermal properties of polymeric materials. Heat transfer within the polymer will be discussed later.

In order to inject the polymer melt accumulated in the front part of the heating barrel into a mold cavity, a plunger pump is equipped in the injection molding machine. The screw in the heating barrel also serves as the plunger in the most of up-to-date injection molding machines. The injection molding machines also have the clamping mechanism for the mold halves. High stiffness is required for the mechanism, since the force to open the mold halves is quite large, e.g. it reaches 10^7 N when the projection area of the product is 0.1 m^2 and pressure of the polymer melt is 100 MPa. Injection molding machines on market are involving the heating barrel system and the mold clamping mechanism as well as the equipment for controlling the temperature of polymer material, amount of melt, injection speed, timing of the operation of each stages, etc.

On the other hand, the mold, which is the heat exchanger for cooling the polymer melt within it as well, used in the injection molding process, is usually made of steel. This is due to the following reasons.

(1) Durability: Shape of products is the transcription of that engraved at the inner surface of the mold. In order to obtain precise products for long duration, therefore, it is important to maintain the shape of the mold, in which highly viscous polymer melt flows at high speed, and from which the solidified products are removed repeatedly. So the mold is usually made of steel or other metals durable for wear due to friction.

(2) Stiffness: In the injection molding process, polymer melt is injected into the mold cavity at extremely high pressure, so as to transcribe the shape of mold cavity precisely. The pressure sometimes reaches upto several hundred MPa in the practical injection molding of polymer. In order to prevent deformation of mold due to the melt pressure, the mold must be made of stiff materials such as steel.

(3) High heat conductivity: As mentioned above, the mold serves as the heat exchanger for cooling of polymer melt within it as well. The mold usually has cooling channels in which a coolant is passing through. In order to cool down the polymer melt effectively, it is desirable that thermal resistance between the cavity surface and the cooling channels. Therefore the mold is mainly made of the material of high heat conductivity, such as metals. Heat transfer dominating the cooling of polymer melt within the mold cavity is not the heat transfer to the coolant flowing through the cooling channels. Details of the heat transfer will be discussed later.

In the next and later lectures, I will discuss why the injection molding process traces the four stages mentioned above, why the present injection molding machines become to have the mechanism and constructions above, how the polymer material behaves under the processing, and what we can do for controlling the behavior of the polymer material, in details.

Problem

Suppose a practical melting processing other than the injection molding of polymers, and investigate the constructions and mechanism of machines used for the processing. Compare the constructions and mechanism to those of the injection molding machine.

Chapter 4
Behavior of Polymer Material under Injection Molding

1. Productivity of the Injection Molding Process

As mentioned in the previous chapter, the injection molding process consists of the following four successive stages: melting stage, filling stage, cooling stage, and demolding stage. Products are continuously produced by performing these four successive stages repeatedly. In order to improve the productivity, therefore, it is necessary to speed these stages as possible. Among these stages, the filling stage and the demolding stage take not so long time by nature, and these stages have little affect on the productivity of the whole process. On the contrary, the melting stage and the cooling stage are generally time-consuming, and thus speeding up these stages result directly in improvement of the productivity.

The reason why the melting and cooling stages consume long time is basically that these stages are related to the heat transfer. In general, thermal diffusivity of the polymeric materials is quite lower than other industrial materials such as metals. Because the thermal diffusivity of polymers is about 3 orders of magnitude smaller than that of metals, heating/cooling of polymers takes time about 3 orders of magnitude longer than the metals if the heating/cooling temperatures for both materials are identical with each other. The heating/cooling time can be shortened by increasing temperature difference between the material and heat source/sink. But it would be a cause of another difficulty especially in heating of polymers. Namely, most of all polymers have the characteristic that temperature difference between the melting temperature and the temperature at which the material starts to degrade is not so large. Therefore, if the temperature of heat source is raised so as to enhance the heat transfer from the heat source to the polymer, material adjacent to the heat source tends to degrade due to overheating; heat transfer in heating the polymeric materials cannot be enhanced so much by raising the heat source temperature. On the contrary, there is no limitation on the temperature difference between the material and heat sink in the cooling of polymer melt, but it is not realistic to use the heat sink at the temperature below the ambient temperature. From these reasons, it can be concluded that the melting and cooling stages are inherently time-consuming as far as the heating/cooling is done by utilizing the heat conduction within the material, and that control of the heat transfer in these stages is the key to the productivity improvement.

2. Enhancement of Heating in the Melting Stage

As mentioned above, "remote" heating due to heat conduction within the material is not suitable for making polymer melt quickly in the melting stage. In the practical injection molding process, consequently, a screw is usually equipped in the heating barrel so as to mixing the material under heating. As shown in Figure 4.1, material adjacent to the inner surface of heating barrel is removed by the thread (called "flight") of screw, so as to prevent the material being overheated, and to make the polymer melt quickly without degrading. Namely convective heat transfer due to polymer motion is usually utilized for enhancing heat transfer in the melting stage[*].

[*] Polymer in the heating barrel is heated also by the heat generated due to friction within the material. Practically, it is estimated that the amount of heat due to the friction is in the same level as that of direct heating from the wall of heating barrel or more. Incidentally, the heating barrel of ancient injection molding machines does not have the screw in it. The heating barrel of ancient injection molding machines used to have a fixed core called "torpedo" instead of the screw in it, so as to enhance heat transfer to the polymer by decreasing the thickness of polymer adjacent to the inner surface of heating barrel. As increasing the melting rate required for the heating barrel, heat transfer enhancement due to the torpedo became insufficient, and thus the screw is getting to be equipped in the heating barrels.

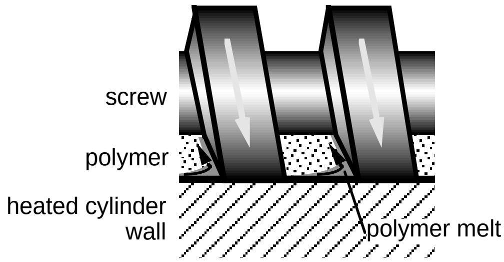

Figure 4.1 Screw in the heating barrel.

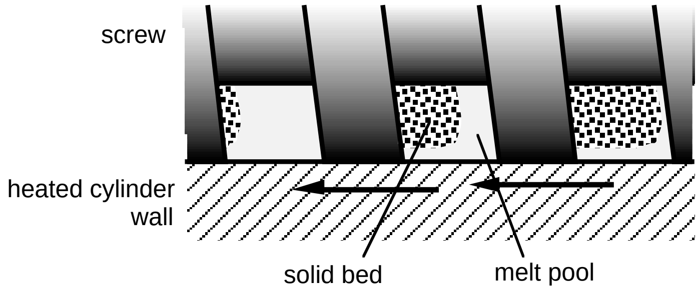

Figure 4.2 Melting of polymer within the screw channel.

Heat transfer in the melting stage and construction of the heating barrel are common to the facilities used in the processing of thermoplastic resin materials. Since the uniformity of both the temperature and the properties of polymer melt produced by the heating barrel directly affects the quality of the products, and the malting rate affects the productivity, melting behavior of polymer material within the screw channel is often investigated by many researchers. For example, Figure 4.2 shows the schema of melting behavior of raw polymer material. Most of all raw polymer materials are supplied in the form of pellets, and thus cluster of the solid materials changes to melt due to heating. At this time, the material starts to melt from its surface adjacent to the inner surface of heating barrel as the matter of course, but the melt is wiped by the flight of screw and thus is accumulated at the leading side of screw flight. When the melt fills the screw channel, the melting stage is completed, but before it, the cluster of un-melted polymer may break (so-called "solid-bed break-up") and the melting behavior becomes complicated.

Indeed the melting behavior in the screw channel is quite complicated, but the heat transfer in the heating barrel is quickened by the motion of screw sufficiently for the practical processing of the polymer products. However, uniformity of the polymer melt produced by the heating barrel system is not always sufficient and therefore the melting behavior in the screw channel is still under investigation for precise molding.

3. Enhancement of Cooling in the Cooling Stage: Behavior of Polymer within the Mold Cavity

As mentioned in the previous section, heat transfer in the melting stage can be enhanced by mixing the polymer material within the heating barrel. On the contrary, it is difficult to quicken solidification of polymer within the mold cavity in the cooling stage, because shape and inner construction of the polymer in the mold cavity have already fixed, and thus it is impossible to mix up the material within the mold cavity. Therefore it can be concluded that the time required for the cooling stage dominates the productivity of injection molding process.

In order to discover a novel method for quickening the cooling of polymer within the mold cavity, one has to understand the behavior of polymer in the mold cavity during the filling and cooling stages. There have been a number of reports concerning the behavior of polymer within the mold cavity in the injection molding process. Some of them show the polymer behavior in the mold cavity visualized through windows installed onto the mold wall. For example, Figure 4.3[1)] shows the mold used for the visualization, and typical polymer behaviors, i.e. polymer melt flow through branched channel, orientation of fiber compounded in the polymer melt, polymer melt flow in a mold having abruptly-changing cross section, and generation of defects on the polymer material, observed by using the mold. The idea that windows are installed onto the mold wall so as to observe the phenomena occurring in the mold cavity is quite simple, but practically speaking, it is not so easy to install the transparent windows onto the mold used in the injection molding. This is because the pressure of polymer melt injected into the mold cavity is quite high as mentioned previously, and thus special devices are required for preventing breakage of window which is usually made of brittle materials such as glass. For example, the mold shown in Figure 4.3 has "wedges" for fixing the glass window, which is compressed by the wedges so as to prevent clacking due to tensile stress generated by the pressure of melt within the mold cavity. If the windows are made of the materials having higher strength for tensile stress than glass, e.g. transparent acrylic resin[2)], the devices for installing the window onto the mold wall can be more simplified.

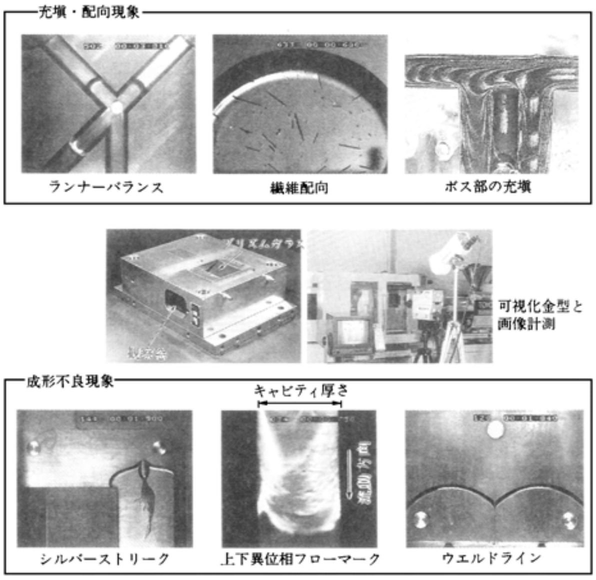

Figure 4.3 Behavior of polymer melt within the mold observed through a visualized mold[1)].

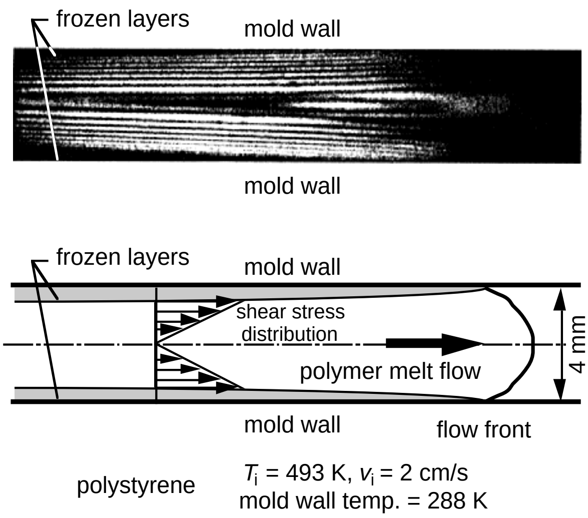

Figure 4.4 Polymer melt flow within the mold cavity in the filling stage[2)].

Figure 4.4[2)] shows the typical flowing behavior of polymer melt within the mold cavity during the filling stage, which was observed through windows installed onto the mold wall. Generally speaking, the gate is narrower than the width of the mold cavity. Otherwise the material filled in the channels in the mold, so-called runner and/or sprue, is hardly separated from the product after the processing. Velocity of the polymer melt flowing in the runner/sprue is therefore higher than that in the mold cavity, but as shown in Figure 4.4, the polymer melt fills the mold cavity from the mold gate (entrance) in order. This is because of the extremely high viscosity of the polymer melt. Inertial force of polymer melt in the runner/sprue is negligibly smaller than the viscous force of it, i.e. Reynolds number of polymer melt flow is extremely low. If the melt injected into the mold cavity slips on the wall, however, the melt spouted out from the gate tends to go straight as is, since viscous force is not generated due to friction between the melt and the cavity wall, and thus the melt in "spaghetti-like" shape fills the mold cavity ("jetting" phenomenon, see Figure 4.5[3)]). This phenomenon results in degrading the quality of products, since the mark of "jetted" material is appeared on the surface of products. In the practical molding process, therefore, injection velocity of the polymer melt and/or "congeniality" between the polymer melt and mold material are carefully selected.

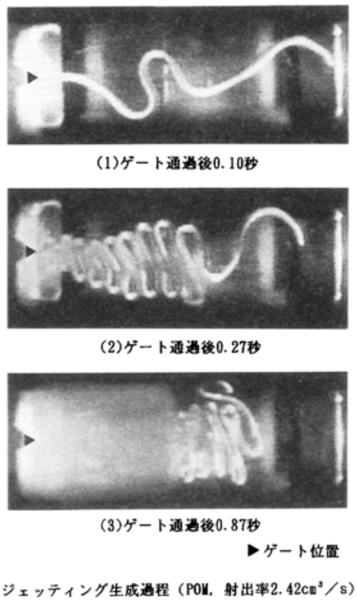

Figure 4.5 Jetting phenomenon[3].

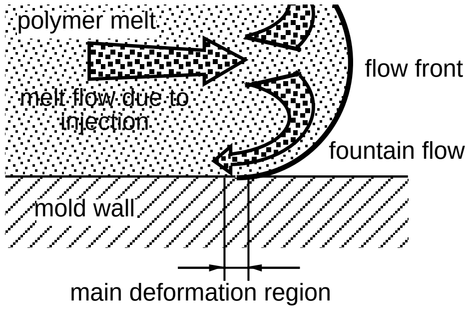

Figure 4.6 Fountain flow at the flow front.

In the normal filling as shown in Figure 4.4, polymer melt flows in the mold cavity with a free surface, called "flow-front." On the flow-front, polymer melt gushes out at the center portion, and moves towards the mold walls, as shown in Figure 4.6. This type of flow is called as "fountain flow." The shape of flow front is usually quite smooth. This is because of the viscoelastic characteristic of polymer melt that the viscosity becomes higher as the melt is elongated by the fountain flow.

As shown in Figure 4.6, deformation of polymer melt has finished on the interface between the mold and the polymer, while the shape of flow front is independent of the shape of the moldings. Therefore it is concluded that preciseness of the molded products is dominated by deformation of the polymer melt occurring around the contact point (line) between the flow front and mold wall. Size of this main-deformation region is hardly affected by the size of moldings. This is the key of the injection molding process by which precise products can be produced irrespective of the size of the products. Actually, deformation of polymer melt in this region is strongly influenced by temperature change of polymer due to heat transfer to the mold wall in the region. The effect of heat transfer on the molding phenomena will be discussed in and after the next chapter in detail.

Problem

Give a precise injection-molded product as an example, and discuss the advantages and disadvantages of the injection molding process for obtaining such a precise product by comparing the molding phenomena in the injection molding process to those of other polymer processing.

References

[1] JSPP ed.: Science of Polymer Processing I "Plasticizing, Forming and Solidifying," (1996) p. 159, Sigma Publishing.

[2] Kurosaki, Y., Satoh, I., Ishii, K.: Trans. JSME, ser. B, 56-522 (1990) pp. 504-511.
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