Paper:

Restraint of Voids Generated Inside Injection Molded Products by In-Mold Pressing Method

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[Received April 25, 2018; accepted July 6, 2018]

In recent years, long glass fiber reinforced plastic and carbon fiber reinforced plastic have begun to be used for structural components that require high strength. As a result, thick-walled injection molded products are being manufactured. However, defects, known as voids, are generated inside the molded product and decrease the strength of the molded product, posing a significant problem at molding production sites. The partial compression method, which is a type of injection compression molding, is effective in preventing voids in thick-walled injection molding. However, there have been limited studies that comprehensively investigated the effects of the compression conditions on void prevention in thick-walled injection molding products or the shape and dimension of the molded product, or the issues in the molded product produced by applying compression. The authors have previously proposed the in-mold pressing (IMP) method, which allows the application of partial compression without the use of an injection compression molding machine and verified its validity. In this study, we proposed a compression device in which a servomotor-driven hydraulic pump actuator is used to propel a movable rod to apply compression to the melt inside the mold cavity. The IMP method using this device was applied to mold thick-walled products with thicknesses of 10 mm and greater, and the effects of compression on the generation of voids inside the molded product and the shape and dimensions of the product were investigated. The results indicate that the generation of voids can be prevented by application of this method. In addition, it was found that marginal deformations, which can pose issues, occur in the molded product when compressive stresses generated inside the molded product by compression are released after demolding.

Keywords: injection molding, in-mold pressing method, thick wall molded product, void

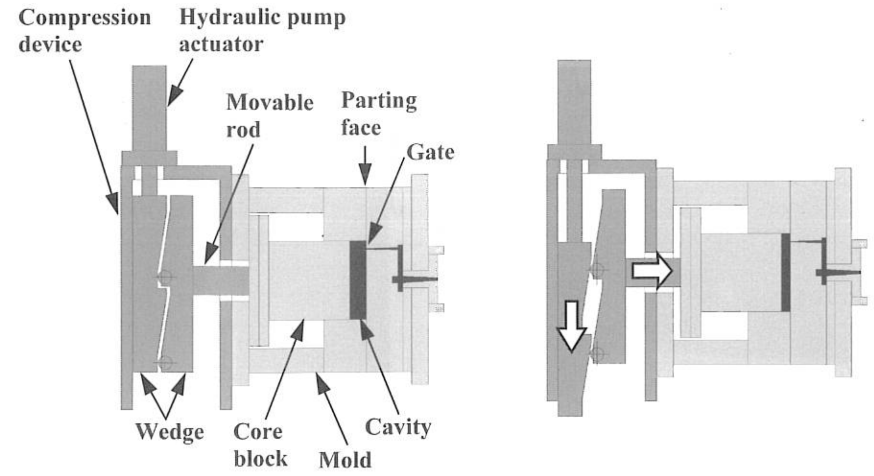
1. Introduction

Because of their light weight and superior formativeness, the application of polymers is increasing in parts that were conventionally manufactured from metals, such as mechanical components, including gears and cams, and exterior parts of automobiles. Furthermore, in recent years, long glass fiber reinforced plastic and carbon fiber reinforced plastic are also being used as structural elements that require high strength [1, 2]. With the increasing demand for higher strength, thick-walled molded products are being manufactured. With the increase in thickness of polymer molded products, voids tend to be generated inside the molded product. Voids are easily generated in injection molding, in particular, as a result of volumetric shrinkage that takes place as solidification of the melt begins in the vicinity of the cavity wall and gradually progresses toward the center [3–6]. Whenever a void is generated inside the molded product, it becomes an internal defect that can cause stress concentrations in the periphery of the void and reduces the strength of the molded product. This has caused significant problems in molding production sites.

One measure to prevent voids from being generated is to apply a significant holding pressure on the melt inside the mold cavity and, therefore, increase the density of the melt. To this end, one can increase the cross-sectional areas of narrow sections of the mold, such as the runner and gate, and employ higher mold temperatures to delay solidification of the melt, allowing the melt to flow into the cavity for as long as possible in order to increase the density. However, the melt may not flow sufficiently into the cavity ends far from the gate, because of decreasing pressure, making it difficult to prevent voids. In addition, the application of significant holding pressures can result in undesirable phenomena such as flashes, residual stresses or strain, or breakage of the mold [7]. Therefore, it is difficult to prevent voids by only the use of increased holding pressure.

Injection compression molding is a molding process in which the melt pressure inside the cavity is actively controlled. Injection compression molding can be broadly divided into three processes: the ROLINX process, injection press molding, and partial compression molding [8, 9]. Injection press molding can be further divided into the injection stamping method and stamping molding. In both the ROLINX process [10] and injection stamping method [11], the cavity is subjected to a low-level cramping force so that the melt filling pressure can open the mold up marginally, or the melt is filled into a cavity that has been marginally widened by opening the mold from the outset, and cramping of the mold is commenced either before or after the cavity is completely filled. While these two methods are reasonably effective in preventing defective transfer and warpage, or reducing birefringence when molding thin products, such as optical disks, they are of limited use with regard to molding thick-walled products. In stamping molding [12], the melt is filled into the mold that is completely open, after which the mold is closed and the cramping force is applied to form the product. This method is primarily used to produce large molded products and has potential applications for thick-walled molded products. However, the process requires a special molding machine, and the fixed and movable sides of the mold must form a faucet fitting structure to prevent flashes because of melt leakage from the mold parting faces, and the faucet fitting part can break during the molding process. In partial compression molding [13–17], an actuator is installed within the injection molding machine or mold and propels a core block to which it is connected to compress the melt into the cavity. This method is used to form optical lenses, or to fill thin sections of molded products, where it is effective in controlling transfer defects, warpage, sink marks, or reducing birefringence. This method can also be used to prevent voids in thick walled molding. However, there have been limited studies that comprehensively examined the effects of the compression conditions on the prevention of voids or the shape and dimensions, and the potential problems caused by compression when it is used to mold products.

The authors have previously proposed the in-mold pressing method (hereafter called the IMP method), that allows the application of partial compression without the use of an injection compression molding machine, and verified its validity [18, 19]. In this study, we propose a compression device that employs a servomotor-driven hydraulic pump actuator to drive a movable rod to compress the melt inside the mold cavity. Using this device to mold a thick-walled product with a thickness of 10 mm or greater, we investigate the effects of compression on the generation of voids inside the molded product and on the shape and dimensions of the product.



(1) Injection process (2) Compression process

Fig. 1. Principle of in-mold pressing method.

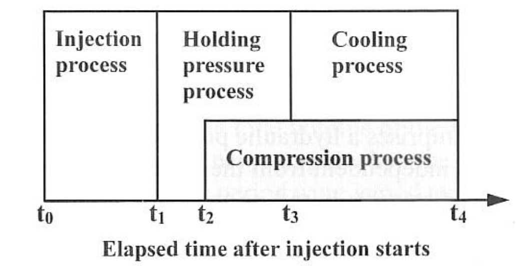
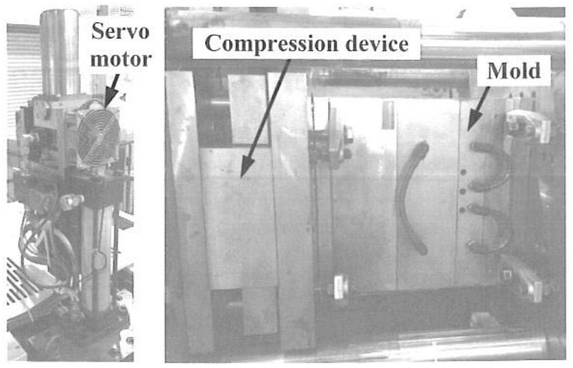


Fig. 2. Time chart for in-mold pressing method.

2. Principle of Molding

Figure 1 shows the principle of molding in the IMP method, and **Fig. 2** shows the time chart of the molding process. The method employs a hydraulic pump actuator (HySerpack, DHA-30W5Q620-FA, Daiichi Denka Corp.), that is driven by an AC servomotor (SGMSH-30ACA21, Yaskawa Electric Corp.), and a compression device that comprises a pair of wedges, attached to the mold to compress the melt inside the cavity. In this device, the vertical movements of the actuator are converted via the wedge mechanism into horizontal reciprocal movements of the movable rod. **Fig. 3** shows photographs of the hydraulic pump actuator and the mold that incorporates the compression device. In the actuator, as opposed to maintaining a constant compression speed, the



(1) Hydraulic pump (2) Compression device and mold

Fig. 3. In-mold pressing device.

compression speed is controlled so that the compression force will not exceed a set value. Abe et al. reported a method [17] that performed injection compression molding, without relying on an injection molding machine, by attaching an injection compression unit (IPM unit) to the movable platen of the injection molding machine. The IPM unit comprises a hydraulic pump and wedge mechanism and is independent from the mold. The device proposed in this study is based on the same principle as the IPM unit. A significant feature of the proposed device, which is similar to the IPM unit, is that it can be easily used with a general-purpose injection molding machine to perform injection compression molding.

The molding process is as follows. First, in the injection process, as shown in **Fig. 1(1)** with times as shown in **Fig. 2**, the melt is injected into the cavity (t_0–t_1). Upon completion of the injection process, the holding pressure process commences (t_1), following which the actuator is driven (t_2) to propel the movable rod, that presses the core block on the movable side of the mold and compresses the melt inside the cavity (t_2–t_4). When the compression process is completed (t_4), the mold is opened, and the product is removed from the mold (hereafter called demolding). The moment that compression starts at t_2 is set later than the gate seal time so that the melt will not flow back from the cavity to the runner when compressed.

3. Experimental Methods

Figure 4 shows the shape of the cavity. In this study, we use a dumbbell-shaped test piece as used in tensile strength tests. In the mold, the entire surface of the core side is compressed by the core block in the direction indicated by the arrow. The gate, that is a pin point gate with a 1.0-mm-diameter, is located on the cavity side. A quartz pressure transducer (Type 6157BA, Kistler Japan Co., Ltd.) is installed on the cavity side to measure the melt pressure inside the cavity. The molding process was performed with a hydraulic injection molding machine (FNX110, Nissei Plastic Industrial Co., Ltd., maximum clamping force: 1100 kN).

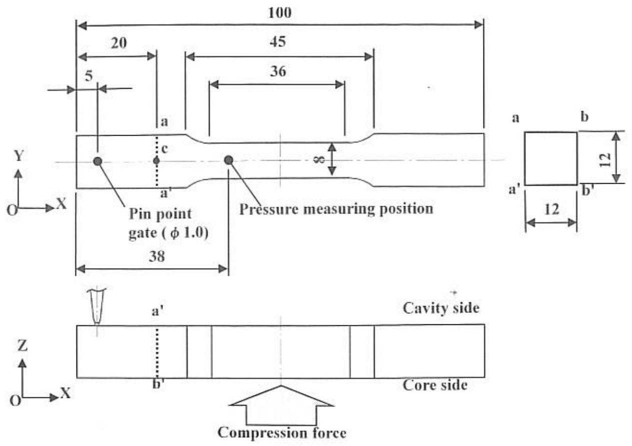


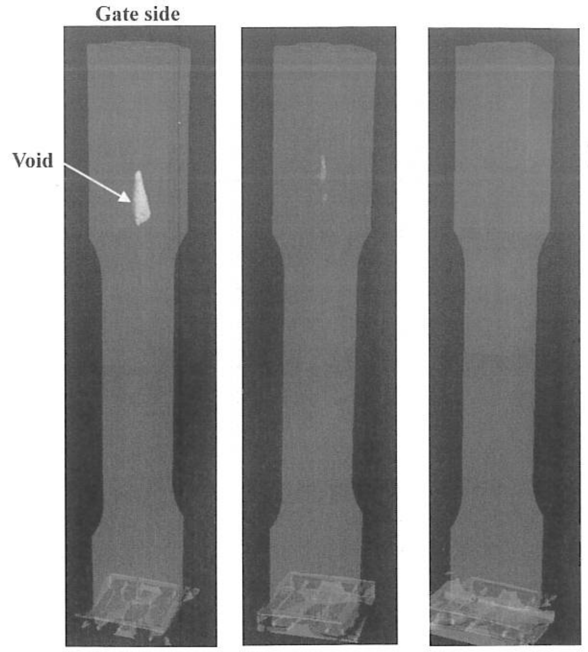
Fig. 4. Cavity shape (unit: mm).

Table 1. Molding conditions.

Molding material	PA66	PA66-GF
Heating cylinder temperature [°C]	275-275-265-265-265	
Mold temperature [°C]	45	
Injection rate [cm^3/s]	12.5	
Holding pressure [MPa]	80	
Compression force [kN]	0, 15, 30, 45, 60, 75	
Compression start time t_2 [s]	8	
Injection time t_0–t_1 [s]	1.6	
Holding pressure period t_1–t_3 [s]	12	
Compression period t_2–t_4 [s]	30, 40, 50, 60, 70	

Two materials were used in the molding experiment: polyamid 66 (Amilan CM3007, Toray Industries, Inc.) (hereafter called PA66) and glass fiber reinforced polyamid 66 (Amilan CM3006G30, glass fiber content: 30 wt%, Toray Industries, Inc.) (hereafter called PA66-GF). **Table 1** presents the molding conditions. The heating cylinder temperature, mold temperature, injection rate, holding pressure, holding pressure period, and compression start time t_2 were held constant, while the compression force and the time from t_2–t_4, during which compression was applied (hereafter called the compression period), were varied. The initial cavity thickness at the time injection was initiated was set at 12 mm. The melt was injected into the 12-mm-thick cavity until it was full, and then compression was applied by the compression device. In this study, we investigated the effect of the compression force and compression period on the generation of voids and the shape and dimensions of the molded product. Five compression forces were used, ranging from 15–75 kN, as shown in **Table 1**. For comparison purposes, normal molding was performed without compression (i.e., compression force 0 kN). To accurately compare the normal molding with the IMP method, a period between 30–70 s, corresponding to the compression period, was set for normal molding (without compression).

To observe the voids inside the molded product, a



(1)Compression force: 0 kN (2)Compression force: 15 kN (3)Compression force: 30 kN

Fig. 5. Observation results of voids in PA66 by X-lay CT scanner (compression period: 70 s).

micro-focus X-ray CT scanner (SMX-225CT-SV, Shimadzu Corp.) was used. The surface shape of the molded product was measured using a non-contact three-dimensional measurement device (VR-3200, Keyence Corp.), to measure the three dimensions a–a', b–b', and a–b, as shown in **Fig. 4**, at the cavity, core, and lateral (or top) sides, respectively. The thickness of the molded product at point c in **Fig. 4** was measured using a micrometer.

4. Results and Discussion

4.1. Void Generation

The generation of voids in the product was observed with the X-ray CT scanner. The images of PA66 under various compression forces with a 70 s compression period were binary coded to extract the void contours, and the voids were color-coded according to volume; the results are shown in **Fig. 5**. In sections where miniscule voids were concentrated, the voids were determined to be connected, making it difficult to determine the volumes of individual voids. Therefore, we limit this discussion to the shape and distribution of voids. In the normal product with 0 kN compression force, a significant void was generated on the gate side. In the case of the IMP method with a 15 kN compression force, although voids were generated in approximately the same positions as the case for 0 kN, they were smaller in size. In the product subjected to a 30 kN compression force, no voids were generated. It was also confirmed that no voids were generated with compression forces of 45 kN or greater. Therefore, with PA66, whereas a single large void was generated in normal molding, it was demonstrated that the application of an increasing compression force using the IMP method initially reduces the size of the voids, and then prevents their generation.

The results of the PA66-GF molded products are shown in **Fig. 6**. In normal molding, where the compression force is 0 kN, a significant number of minute voids were distributed over the entire area of the molded product. In particular, a significant number of voids were generated in the wider sections of the product. In the IMP method with a compression force of 15 kN, although voids were prevented in the narrow section of the product, a significant number of voids were observed in the wider sections. The number of voids decreased with increasing compression force, and they were completely eliminated when 60 kN was used. Therefore, it was found that a significant number of miniscule voids were generated in the PA66-GF, that contains glass fibers, and that a compression force higher than in the case of PA66 was required to eliminate these voids.

From the results shown in **Figs. 5** and **6**, the volumes of the voids were summed to determine the ratio of the void volume against the total volume of the molded product. The void volume percentages when the compression force and compression period were varied using PA66 and PA66-GF are presented in **Tables 2** and **3**, respectively. In **Table 2** the voids decrease at higher compression forces and longer compression periods. Therefore, increasing the compression period is particularly effective in eliminating voids. In **Table 3** the voids are eliminated at a compression force of 60 kN or greater, regardless of the compression period. Although the void volume percentage gradually decreases with longer compression periods, it can be seen that increasing the compression force is more effective than lengthening the compression period to eliminate voids.

The above results indicate that the use of the IMP method prevents voids, that are generated with normal molding, regardless of the void size, number, or distribution, and also indicates the effects of compression force and compression period on the prevention of voids.

4.2. Melt Pressure Inside Mold

The cavity pressure profiles measured at the position indicated in **Fig. 4** using the quartz pressure transducer are shown in **Fig. 7**. For both molding material types, the profiles of normal molding, with 0 kN compression force, and those for the IMP method where compression forces of 15 kN and greater were applied for 70 seconds, are compared. In normal molding, with 0 kN compression force, the melt pressure increases abruptly when injection is initiated (A). At some point during the subsequent holding pressure process, the gate is sealed, causing the pressure to decrease sharply, falling to zero at approximately 14–22 s. Using the IMP method for both molding material types, with compression forces of 15 kN and greater, the melt pressure displays a profile that is similar to normal

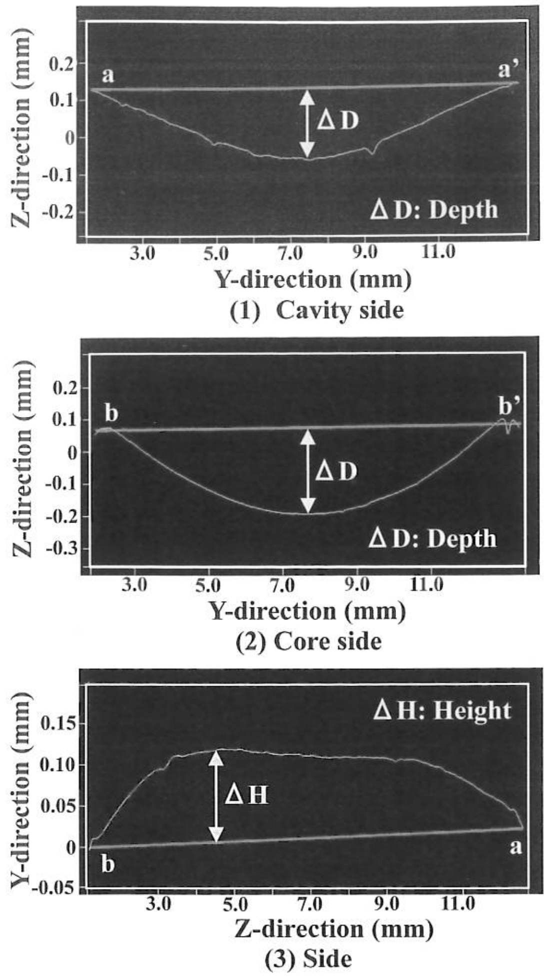


Fig. 9. Surface profiles of PA66 molded product (compression force: 75 kN, compression period: 70 s).

riod for the IMP method. This suggests that, in order to produce a molded product with the desired thickness, it is necessary in this method to first investigate the relationship between the initial cavity thickness, compression force, and compression period, according to the molding material type.

4.4. Surface Shape of Molded Product

Figure 9 shows the measurement results of the shapes of the surfaces of the molded product on the cavity, core, and lateral sides. As an example, the measurement results are shown for the PA66 product obtained when a compression force of 75 kN was applied for 70 s. The surfaces on the cavity and core sides, shown in **Figs. 9(1)** and **(2)**, respectively, exhibit curved depressions with the lowest point close to the center. By contrast, the surface on the lateral side, shown in **Fig. 9(3)**, exhibits a bulging surface that is more pronounced toward the core side b. These trends were also observed under the other conditions. The relationships between the depth ΔD on the cavity and core sides, the height ΔH of the swelling on the lateral side, and the compression force and period were investigated. The relationships between the compression

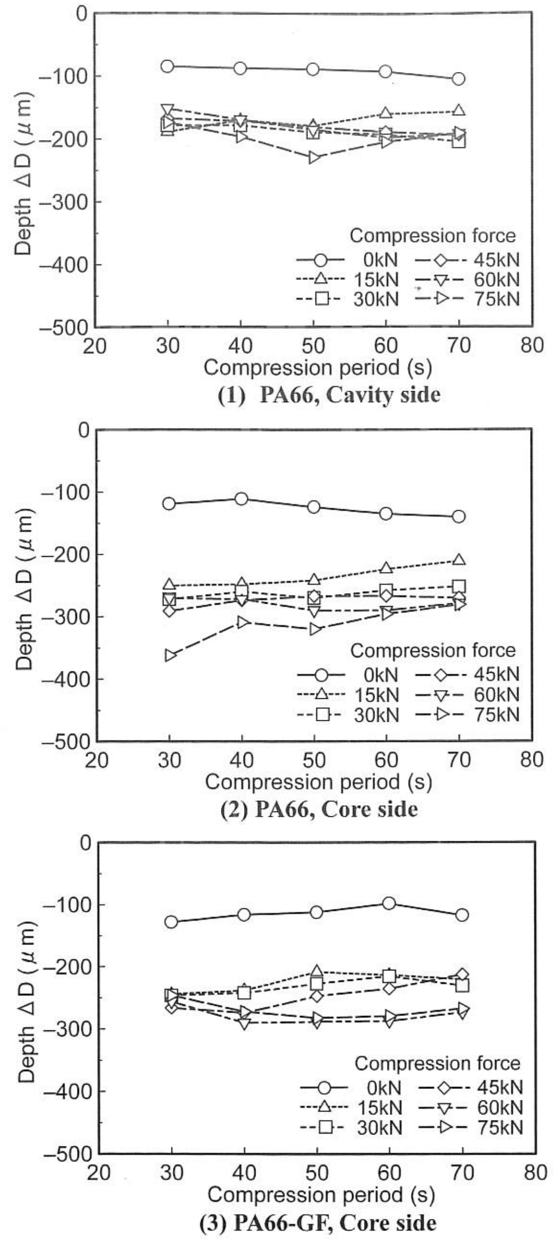


Fig. 10. Relationships between depth ΔD and compression period for various compression forces.

force and period and ΔD and ΔH are shown in **Figs. 10** and **11**, respectively. In **Fig. 10**, only the measurement results for the core side are shown for PA66-GF. It can be seen that the magnitude of ΔD is smallest for normal molding, with a compression force of 0 kN, regardless of the molding material type or whether on the cavity or core sides. For the IMP method, at 15 kN and greater, the magnitude of ΔD typically increases with increasing compression force. In addition, the magnitude of ΔD is greater on the core side than on the cavity side. In **Fig. 11**, that shows the results of the lateral side, ΔH is negative for normal molding, with the surface being indented. However, for the IMP method it is positive, forming a bulging surface. In addition, ΔH exhibits a general increase with increasing compression force. Therefore, for normal molding, all

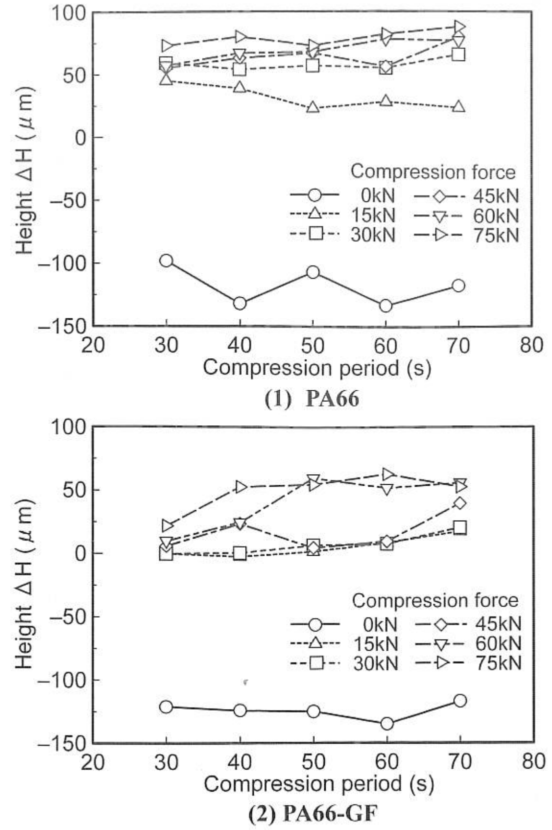


Fig. 11. Relationships between height ΔH and compression period for various compression forces.

surfaces of the molded product are depressed. However, for the IMP method, the surfaces on the cavity and core sides are depressed and the lateral side bulges outward. The causes of this are discussed below.

As can be seen in **Fig. 12(1)**, for normal molding, solidification of the melt progresses from the cavity wall toward the center, and the melt volume shrinkage produces sink marks on all surfaces of the product. For the IMP method, however, compressive stresses are generated inside the molded product because of compression. When the compressive stresses are released with demolding, we surmised that swelling would occur on all surfaces. However, as can be seen in **Fig. 10**, in actual fact, although swelling occurred on the lateral side surface, the surfaces on the cavity and core sides were depressed. In addition, although the pressure profiles of **Fig. 7** indicate that a significant pressure acts on the sensor mounted on the cavity-side wall right up to demolding, the surface of the molded product on the cavity side is depressed; therefore, an apparently contradictory result is obtained, where it appears that the melt is not in contact with the sensor. Therefore, we surmise that the causes of the surface shape resulting from the IMP method are as follows. When compression is initiated, equal compressive displacements occur at both ends (i.e., left and right) as well as in the middle section. At the ends, the melt is subjected to compression when it has mostly solidified, as shown in **Fig. 12(2)**, thereby increasing the stiffness and generating significant compressive stresses. However, in the middle section, where solidification takes place later, that generates a condition in which the solid and liquid phases coexist, the compressive displacements are partially absorbed by the volume shrinkage that takes place when the melt crystallizes, so that the compressive stresses are lower than at the ends. These compressive stresses are released when the product is demolded, so that the ends with higher compressive stresses expand more than the middle section with lower compressive stresses, generating depressed surfaces on the cavity and core sides. On the lateral sides, swelling occurred because of the release of compressive stresses, and it was more pronounced in sections closer to the core side that were affected to a greater degree by the compressive force and, therefore, subjected to higher compressive stresses.

As discussed above, for the IMP method, the compressive stresses generated by compression inside the molded product were released after demolding and affected the shape and dimensions of the product. This is a phenomenon that can occur in not only the IMP method but other partial compression methods as well, suggesting that it is necessary to investigate compression conditions that can minimize the shape and dimensional errors as well as the cavity and core surface shapes that can cancel out these errors.

5. Conclusion

We investigated the effect that the IMP method has on the generation of voids in thick-walled molded products and on the shape and dimensions of the molded product. The findings are listed below.

(1) We verified empirically that the use of the IMP method can prevent the generation of voids regardless of their size, number, and distribution. In addition, we determined the effects that the compression force and period have on the prevention of voids.

(2) We measured the melt pressure that indicated that, for the IMP method, a significant melt pressure was maintained for a long period inside the cavity. We surmise that this melt pressure prevented the generation of voids.

(3) Using PA66, in which a single large void was generated under normal molding, continuous long-term application of compression until the melt completely solidifies has the effect of preventing voids. With PA66-GF, in which significant numbers of miniscule voids were generated for normal molding, the short-time application of a significant compression force has the effect of preventing voids.

(4) It was found that depression and swelling of the surface of the molded product occurred with the IMP method. In the discussion, we surmised that this was caused by the release of compressive stresses generated inside the molded product by compression.

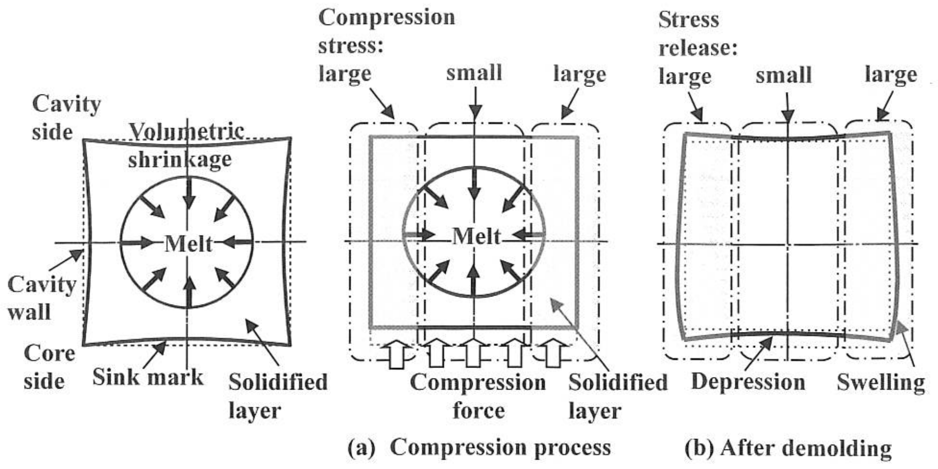


Fig. 12. Deformation generating mechanism in molded product surfaces.

In summary, although there remain issues regarding the accuracy of the final shape and dimensions of the molded product, the IMP method can be applied to produce thick-walled structural components, in which the generation of voids may reduce the mechanical strength, as long as the above issues do not pose significant problems. Polymer components that undergo secondary processing, such as plates, rods, and blocks, have conventionally been mass-produced by injection molding [20]. However, this method is unsuitable for small-lot multi-type polymer production. The present method is suitable for small-lot production of polymer components and has good prospects for future applications in the production of void-free polymer blocks.

Acknowledgements

The authors wish to express their gratitude to Nissei Plastic Industrial Co., Ltd., who extended their cooperation in the modification of the injection molding machine.

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Membership in Academic Societies:
- Japan Society of Polymer Processing (JSPP)
- Japan Society for Die and Mould Technology (JSDMT)
- Japan Society for Precision Engineering (JSPE)
- Japan Society for Technology of Plasticity (JSTP)
- Japan Society for Design Technology (JSDE)
- Polymer Processing Society (PPS)