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Relationship between Fine Replication and Low Transmitted Wavefront Error ofoptical Plastic Parts in Injection Moldng

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Abstract: In this study, we investigated the cause of compatibility problem between fine transferability and transmitted wavefront aberration which is a problem in injection molding of plastic optical element.The relationship between the processing parameters, the quality of the sample, and the pressure in the mold was investigated using a mold of an antireflection structure.As a result, mold temperature and holding pressure are important to obtain high transfer rate, but high holding pressure markedly deteriorates transmitted wavefront aberration.This reason is that the pressure remaining in the mold before the mold opening increased the resistance on ejection process and the surface was deformed.The low mold temperature caused a difference in cooling rate, the mold shrinkage became non-uniform, and the transmitted wavefront aberration deteriorated.

Keywords: injection molding, nano molding, antireflection structure, replication, wavefront, residual pressure

I. INTRODUCTION

In the optical industry in recent years, there is an increasing need for mass production of complex optical elements with fine structures on its surface. Forming fine structure on the surface of lens, such as antireflection, polarization separation structure and microlens array [1], can reduce the number of parts, so that it is possible to reduce the size and the assembly cost of unit. Also in terms of function, for example, the antireflection structure has advantages such as less incidence angle dependence and wavelength dependency and higher environmental reliability than antireflection coating with multilayer.

Injection molding [2-3], one of the most popular techniques, is well-suited for manufacturing plastic products with complicated and precise shapes in a short cycle. However, since the molten resin is rapidly cooled from the moment of contact with the mold surface and its viscosity increases, there is a problem that transfer to the microstructure is easily hindered. It is generally known that the surface temperature and the pressure applied to the surface are important for achieving fine transfer. However, experience has shown that increasing mold temperature and pressure will degrade other quality of lens such as surface accuracy and wavefront aberration. Therefore, it is difficult to satisfy both the quality and the molding transfer. In the field of fine transfer molding, there are few cases reporting this compatibility problem in detail.As a method of fine transfer molding, thermal imprinting [4] and a new molding method [5-6] are also effective, but they are less productive than injection molding, and there are considerable restrictions on shapes that can be molded.

In this research, we investigated the relationship between transmission accuracy and transmission wavefront distribution, which is a problem in injection molding of optical elements with fine structure on the surface. First, we investigated the effect of molding parameters on transferability using a mold of antireflective structure (ARS), and examined the tendency of transmitted wavefront aberration with respect to mold temperature and holding pressure, which were greatly influence transferability. We examined the relationship between shape accuracy of both sides, residual stress, and pressure inside the mold, and discussed the mechanism of deteriorating transmitted wavefront aberration.

II. MATERIALS AND METHODS

A. Injection Molding

Fig. 1 shows a schematic drawing of sample molded by experiment. The diameter is 4.4 mm, and the thickness is 0.6 mm. The mold piece had a stainless steel body and its surface coated with Ni-P by electroplating was polished. ARS was fabricated on the mold surface by a lithography technique: etching was conducted after electron-beam printing on the resist-coated Ni-P surface. The pattern consists of a number of convex shapes arranged in a hexagonal close-packed lattice, and the minimum distance between each lattice was set to about 0.3 nm. The pattern of mold was evaluated with a scanning electron microscope (SEM) and an atomic force microscope (AFM). They are shown in Fig. 2.

Fig. 3 shows the schematic cross section of the mold construction. After the mold opened, the molded product was ejected from the mold with the mold insert and each pin arranged at the runner. In order to investigate the change of the pressure in the mold, called as the cavity pressure, a quartz piezoelectric type internal pressure sensor 9213B (Nippon Kistler Co., Ltd.) was mounted on the stationary side of the mold as shown in Fig. 3.

As a molding material, cyclo olefin copolymer APL5014DP (Mitsui Chemicals, Inc., glass transition temperature of around 135 ^{o}C, melt flow rate of around 36 g/10 min. at 260 ^{o}C) which has good birefringence and is generally used for optical applications was used. An electric injection molding machine SE-50D (Sumitomo Heavy Industries, Ltd.) was used for molding samples. This machine had a maximum clamping force and screw diameter of 50 tons and 22 mm, respectively. The molding parameters are listed in Table 1. By using the transfer glass temperature (Tg) of the polymer as the standard, the mold and nozzle temperature were set. Note that the resin temperature of 300 ^{o}C exceeds the manufacturer's recommended range, but it was set for comparison.

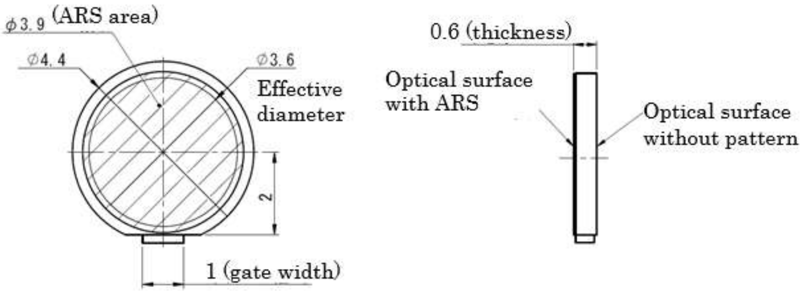
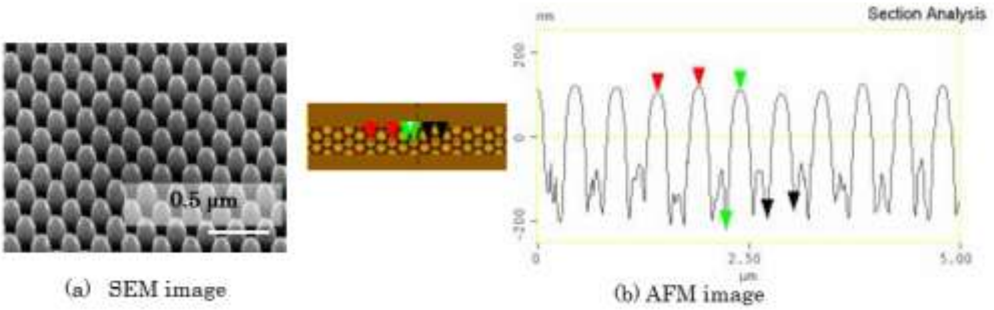


Fig.1: Schematic drawing of molded sample in experiment



(a) SEM image

(b) AFM image

Fig.2: Evaluation results of anti-reflection structure fabricated on the mold surface

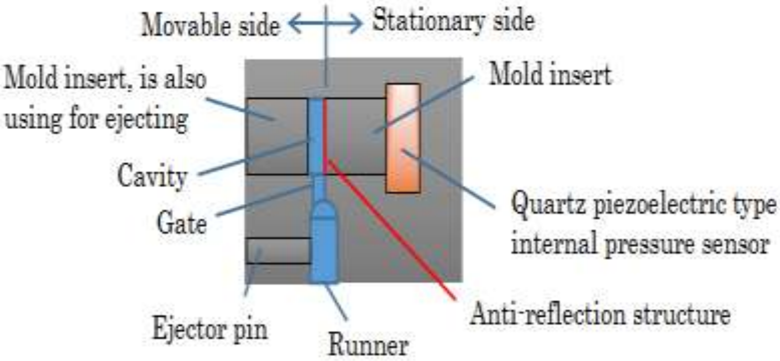


Fig.3: Schematic structure of mold

Table I: Molding conditions

Resin temperature (°C)	280*, 300
Mold temperature (°C)	125, 135*
Injection speed (mm/s)	5, 10*, 20, 50
Holding pressure (MPa)	20*, 40, 60
Cooling time (s)	25

* Selected as the standard molding parameter

B. Evaluation

We measured the profile of transferred antireflection structure using AFM. We define the transcription ratio *R* using the following equation:

$$R = H_s / H_m \times 100 \quad (1)$$

where H_s and H_m represent the height of mold and sample, respectively.

The transmitted wavefront distribution and the reflected wavefront distribution of the samples were evaluated using a Fizeau interferometer with He-Ne laser VeriFire PE (Zygo Corporation). The transmitted wavefront distribution represents the phase difference between the light reflected from the reference plane and the light transmitted through the sample.

The reflected wavefront distribution represents a shape error which is determined as the phase difference between two lights reflected at each surface of sample and reference plane, respectively. To investigate the residual stress within the samples, a birefringence measuring instrument WPA-100 (Photonics Lattice, Inc.) was used.

III. RESULTS AND DISCUSSIONS

Effects Of Molding Process Parameters On Transferability

First, the influence of molding conditions on the transferability of ARS was investigated. Fig. 4 shows relationships between transcription ratio and injection speed when molding was performed at different resin temperatures. In order to investigate the dependency of injection speed, the mold temperature was 125 °C, which is susceptible to the influence of cooling during flow.In the case where the injection speed was extremely slow as 5 mm/s, when the resin temperature was low, the transcription ratio was as low as about 10%, but it improved when the resin temperature is high.

As a result of examining the relationship with cavity pressure measured,it was found that the integration value of the pressure and the transcription ratio have a relatively good correlation under the condition that the injection speed is 20 mm/s or less.On the other hand, when injection speed was extremely too fast as 50 mm/s, the transcription ratio showed a tendency to decrease.This is probably because air in the mold was not vented sufficiently during the resin filling too quickly, and the gas pressure increasing inside the mold suppressed transcription to the structure on the mold [7]. On the other hand, when the resin temperature was 300 °C, the dependency of the injection speed became small.

This reason was that high resin temperature suppressed decrease of cavity pressure due to cooling and solidification at the gate portion, which tends to occur at low speed filling. Also, in the case of high-speed filling, the peak of caivty pressure was higher by about 5 MPa than when the resin temperature was low. It was considered that the screw of the molding machine could not be stopped immediately and the pressure increased.It is generally known that transcription is improved when the injection speed is increased.

However, in the case of this experiment, since the size of the molded product is small, it is considered that the filling speed should be fast enough to reduce the influence of cooling from the mold.

Next, the transcription ratio of each sample molded by changing the mold temperature and holding pressure is shown in Fig. 5. When the mold temperature was low, the transcription ratio improved as holding pressure being increased, but it remained around 40%. When the mold temperature was high, the transcription ratio increased as a whole, but similarly it showed a tendency to cease with respect to the holding pressure and stayed at about 50%.

The degree of influence on the transcription is much greater than in the case of changing the resin temperature and injection speed.

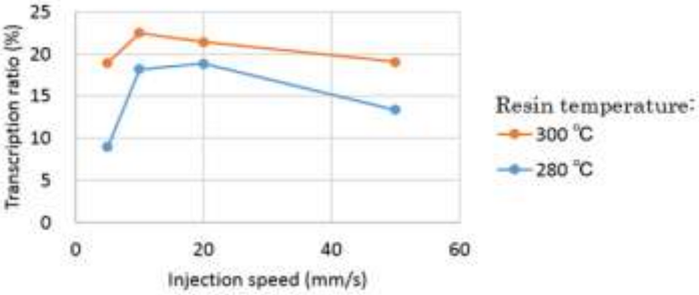


Fig.4: Relationships between transcription ratio and injection speed when molding was performed at different resin temperatures

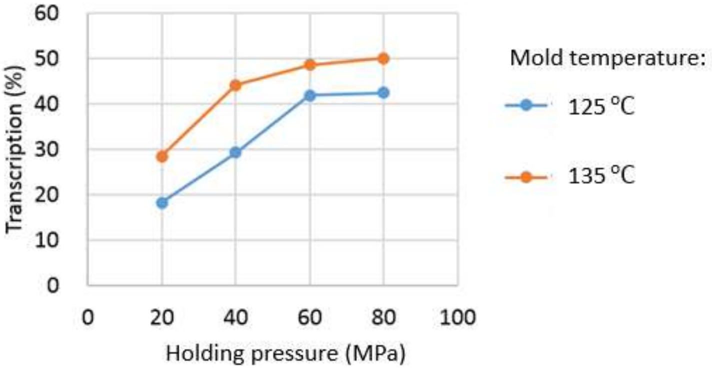


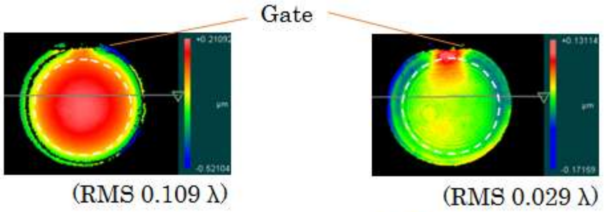
Fig.5: Relationships between transcription ratio and holding pressure when molding was performed at different mold temperatures

A. Influence of mold temperature on transmitted wavefront distribution

Fig. 6 shows the transmitted wavefront distribution of each sample molded by changing the mold temperature. The broken line in the figure shows the effective diameter. The red region indicates that the phase is faster. When the mold temperature was low, the phase of the light was faster at the center of the lens, and a concentric distribution was observed. Values in parentheses represent the root mean square (RMS) of the deviation from the ideal wavefront within the effective diameter, which is called RMS wavefront aberration. In this case, the deviation from the reference plane is shown, and in the ideal case, it is uniform distribution. When the mold temperature was high, although the phase was slightly disordered near the gate, the phase was uniform as a whole as compared with the case where the mold temperature was low.

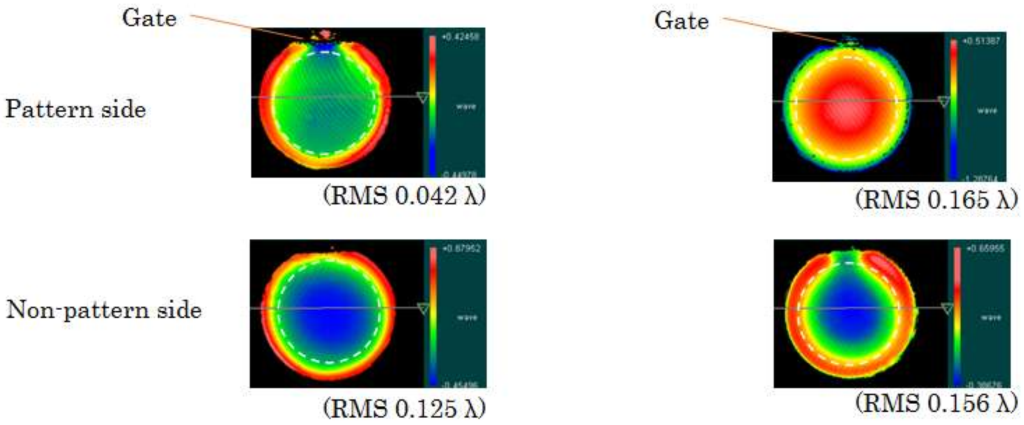
Next, to examine the influence on the transmitted wavefront in more detail, the shape accuracy of both sides of each sample shown in Fig. 6 was investigated. The evaluation results of the reflected wavefront distribution are shown in Fig. 7. The distribution shows the shape error with respect to the reference plane set in the interferometer, indicating that the phase is faster and the shape is swollen in the red region. When the mold temperature was low, both sides have a slightly concave shape at the center, which was thin at the center and slightly thick at the outer circumference. Therefore, the phase of the transmitted light was fast in the central part and slow in the peripheral part, so it was thought that the distribution was concentric distribution as shown in Fig. 5 (a). Even when the mold temperature was high, there was shape error on both sides, but both surfaces had about the same degree of error, one of which had a convex shape and the other a concave shape. So, it was thought that warp deformation had occurred, and the influence on the phase difference of the transmitted light was reduced.

To investigate this phenomenon in detail, Fig. 8 shows the evaluation results of the magnitude and direction of birefringence. This birefringence is generated as anisotropy of the refractive index as a result of cooling the polymer molecular chains aligned by the stress generated during molding, and the magnitude and direction of the residual stress in the sample can be estimated. As indicated by arrows in Fig. 8 (a), when the mold temperature was low, residual stress was observed near the edge of the outer circumference, and the direction was in the radial direction. Based on the above, the estimated mechanism that the difference in mold temperature affects the transmitted wavefront distribution is shown in Fig. 8. Low mold temperature increased the difference in cooling rate between the outer peripheral part and the central part. Therefore, the shrinkage behavior became non-uniform, and as a result of the difference in thickness, the transmitted wavefront aberration deteriorated.



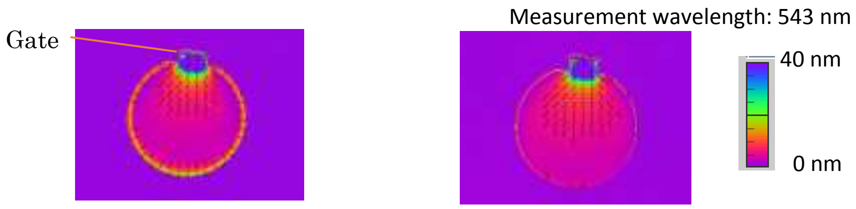
(a) Mold temperature: 125 °C (b) Mold temperature: 135 °C

Fig.6: Transmitted wavefront distribution of samples molded with different mold temperatures (resin temperature of 280 °C, injection speed of 10 mm/s and holding pressure of 20 MPa)



(a) Mold temperature: 125 °C (b) Mold temperature: 135 °C

Fig.7: Reflected wavefront distribution of each surface of samples shown in Fig. 6



(a) Mold temperature: 125 °C (b) Mold temperature: 135 °C

Fig.8: Birefringent phase distribution of each sample shown in Fig. 6

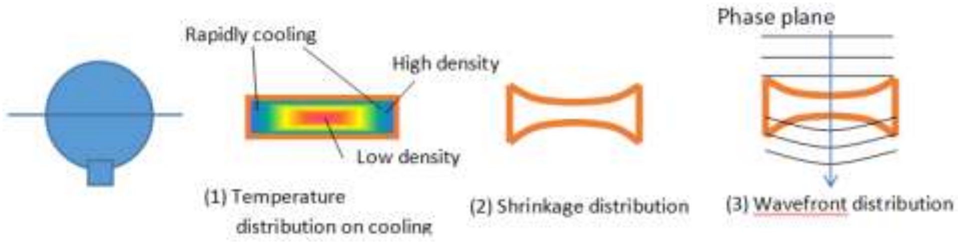


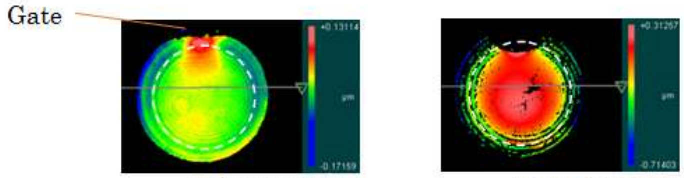
Fig.9: Mechanism that low mold temperature influences the transmitted wavefront distribution

B. Influence of cavity pressure on transmitted wavefront distribution

Next, Fig. 10 shows the transmitted wavefront distribution of each sample molded by changing holding pressure. Also, Fig. 11 shows the reflected wavefront distributions on both sides of these samples. As the holding pressure was increased, the distortion increased from the gate to the central part of the sample in the distribution of the transmitted wavefront. Particularly when the holding pressure was 60 MPa, the wavefront deteriorated so much that interference fringes on the outer peripheral part could not be read. In addition, even when the mold temperature was changed, the same tendency as the holding pressure was observed.

In order to clarify the cause, we investigated the difference in cavity pressure when holding pressure was changed. The results are shown in Fig. 12. When the resin reached the end of the product part in the mold, the pressure in the mold rapidly increased since it can not be filled more easily. While a constant pressure being applied to the screw, the transmission of pressure was weakened by rapid cooling of the gate, and the pressure in the mold was reduced correspondingly. Increasing the holding pressure naturally raised the pressure peak, but the high pressure was still loaded until the mold was opened. Therefore, we focused on the pressure remaining in the mold, and investigated the relationship with the transmitted wavefront aberration. The results are shown in Fig. 13. The pressure at the time of mold opening 5 seconds before was used as its value. Hereinafter, it is referred to as 'in-mold residual pressure' or only 'residual pressure'. As the residual pressure became smaller, the transmitted wavefront aberration showed a tendency to improve. However, when the residual pressure falled below a certain value, sink marks were generated on the surface, and the transmitted wavefront aberration was remarkably deteriorated. This means that the pressure enough to compensate for the shrinkage of the resin was insufficient. Also, when the mold temperature was high, the minimum of residual pressure that caused no sink markedness became small. It is generally known that this type of sink is caused by partial release from the mold while cooling process. Therefore, when the mold temperature was high, the adhesion between the mold and the resin was strengthened, so that it was thought that partial release in the mold was suppressed.

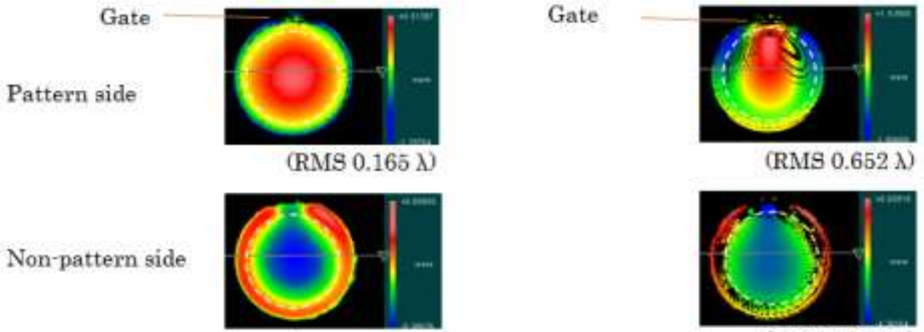
In order to investigate how the residual pressure in the mold was related to the molding process, we evaluated the birefringence distribution of the sample. The results are shown in Fig. 14. When the holding pressure was high, stress originating from the gate side remained, and it is considered that molecular orientation was caused by pushing in with high pressure while cooling the resin. In addition, a strong birefringence was seen at the edge of the outer peripheral part. Therefore, when observing the side portion of the sample with a laser scanning microscope (LSM), there were many scratches on the side of samples molded with the holding pressure high. Fig. 16 shows the mechanism causing this phenomenon. The scratches on the side indicated that the ejecting resistance was large. Because the side of sample was no draft, the high internal residual pressure without relaxation increased the resistance. On the other hand, since the draft angle of the runner was sufficient, it was ejected slightly before the gate. Therefore, it seemed that deformation occurred mainly from the gate to the center of sample.



(RMS 0.029 λ) (RMS 0.219 λ)

(a) Holding pressure: 20 MPa (b) Holding pressure: 60 MPa

Fig.10: Transmitted wavefront distribution of each sample molded by changing holding pressure (resin temperature of 280 °C, injection speed of 10 mm/s, mold temperature of 135 °C)



(RMS 0.165 λ) (RMS 0.652 λ)

(RMS 0.156 λ) (RMS 1.079 λ)

(a) Holding pressure: 20 MPa (b) Holding pressure: 60 MPa

Fig.11: Reflected wavefront distribution on each surface of samples shown in Fig. 10

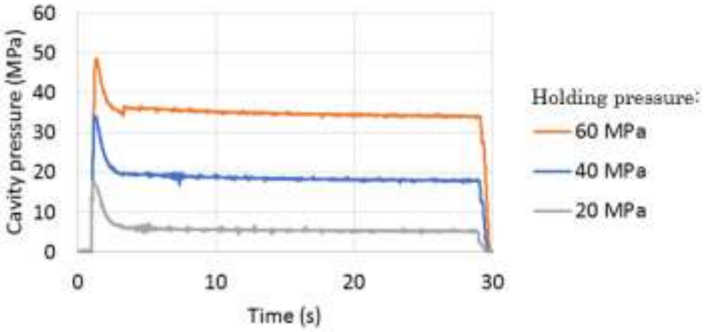


Fig.12: Changes in cavity pressure with different holding pressures(resin temperature of 280 ^{o}C, injection speed of 10 mm/s, mold temperature of 135 ^{o}C)

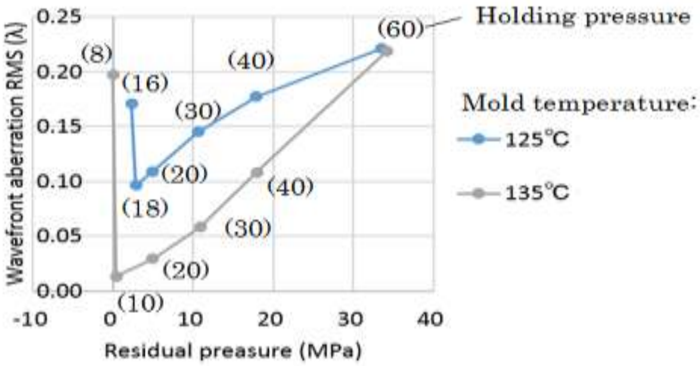
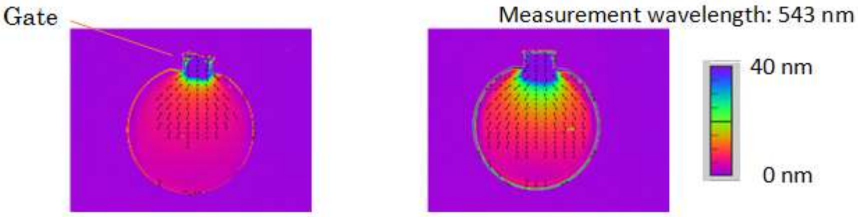
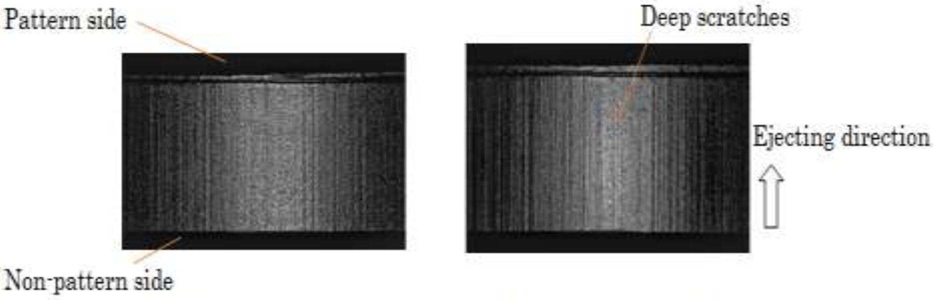


Fig.13: Relationship between transmitted wavefront aberration of each sample and in-mold residual pressure when molding was performed by changing mold temperature and holding pressure



(a) Holding pressure: 20 MPa (b) Holding pressure: 60 MPa

Fig.14: Birefringent phase distribution of each sample shown in Fig. 10



(a) Holding pressure: 20 MPa (b) Holding pressure: 60 MPa

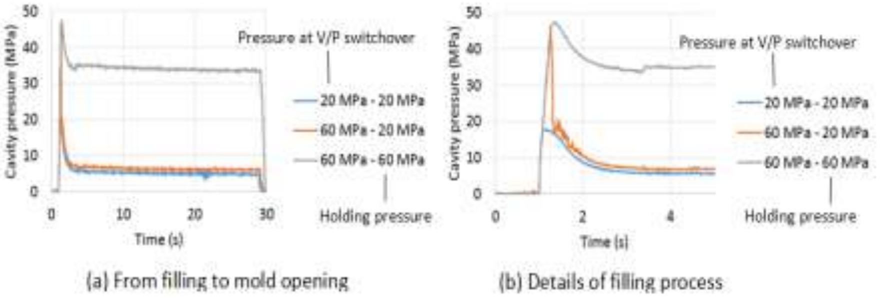
Fig.15: Images of side surface of samples shown in Fig. 10 with a laser scanning microscope

Fig.16: Mechanism that the in-mold residual pressure causes the deformation of sample

C. Possibility of both fine transcription and low transmitted wavefront aberration by peak pressure control

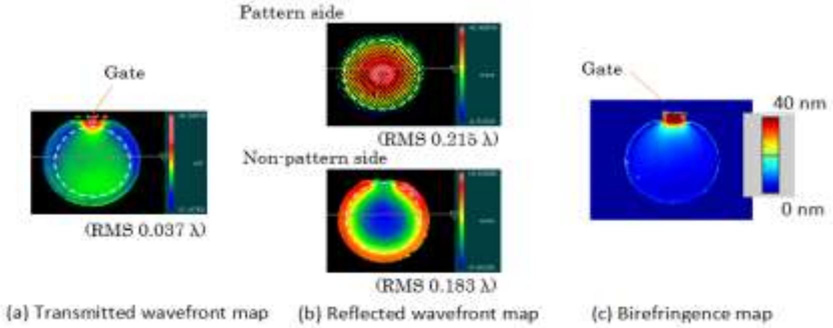
As a result, it was found that although high pressure is required to improve the transcription, it is necessary to reduce the pressure during cooling to suppress transmitted wavefront aberration. Therefore, we examined the difference by changing the pressure at velocity/pressure (V/P) switchover of the screw. V/P switchover is the transition from filling stage to packing stage during injection cycle. In the pressure switching mode, when the set pressure is exceeded during the filling step, the screw can be switched from speed control to pressure control, and the pressure peak can be arbitrarily controlled. The change of cavity pressure when changing only the pressure at V/P switchover while the holding pressure set 20 MPa, which is low enough not to generate sink marks, is shown in Fig. 17. The maximum value of the in-mold pressure changes according to the set switching pressure. However, since the screw then switches to the low hold pressure set, the pressure in the mold immediately declined and remained low until the mold opened. While keeping the residual pressure in the mold low, the maximum value of the in-mold pressure varies according to the set switching pressure. The evaluation results of samples molded with VP switching pressure of 60 MPa are shown in Fig. 18. Compared with the case where the holding pressure is high as shown in Fig. 10 and Fig. 11, the distortion of the gate side was reduced and it was confirmed that the deformation was suppressed. Also, Fig. 19 shows relationship between transmitted wavefront aberration and residual pressure. In this case as well, good correlation was found between them.

Fig. 20 shows the trend of the transcription ratio. Although the improvement tendency was shown when only the pressure at VP switchover was increased, the effect was smaller than when the holding pressure was increased. Therefore, it was found that a high pressure was necessary for improving the transfer rate and it was necessary to apply a certain time or more.



(a) From filling to mold opening (b) Details of filling process

Fig.17: Comparison of cavity pressure by changing the pressure at V/P switchover and the holding pressure



(a) Transmitted wavefront map (b) Reflected wavefront map (c) Birefringence map

Fig.18: The evaluation results of samples molded with VP switching pressure of 60 MPa, holding pressure of 20 MPa

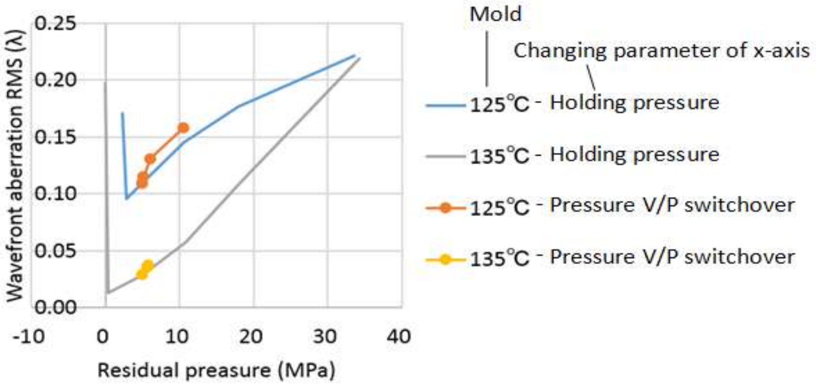


Fig.19: Relationship between transmitted wavefront aberration of each sample and in-mold residual pressure when molded by changing mold temperature and holding pressure

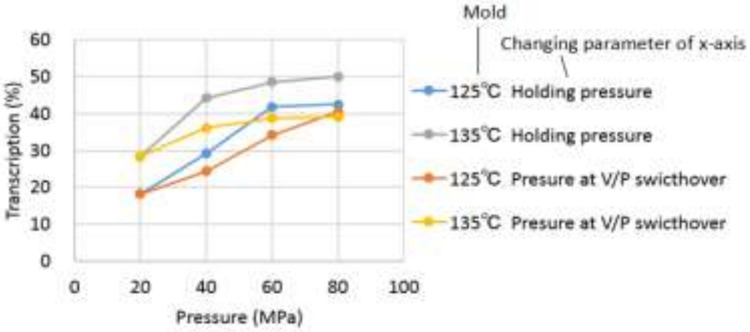


Fig.20: Transcription ratio by changing the holding pressure and the pressure at V/P switchover at each mold temperature

IV. CONCLUSIONS

In this research, we investigated relationship between fine transcription and low transmitted wavefront distribution, which is a problem in injection molding of optical elements with fine structure on the surface.First, we investigated the effect of molding parameters on transferability using a mold of antireflective structure, and examined the tendency of transmitted wavefront aberration with respect to mold temperature and holding pressure, which were greatly influence transferability.We examined the relationship between shape accuracy of both sides, residual stress, and cavity pressure, and discussed the mechanism of deteriorating transmitted wavefront aberration. Conclusions found in this paper can be summarized as followings:

- In order to raise the transcription ratio, it is necessary to fill the resin with a high mold temperature condition and apply a high holding pressure.
- Low mold temperature increased the difference in cooling rate between the outer peripheral part and the central part. Therefore, the shrinkage became non-uniform, and as a result of the difference in thickness, the transmitted wavefront aberration deteriorated.
- The high holding pressure markedly deteriorated the transmitted wavefront aberration. There was a clear relationship between the pressure remaining before the mold opening and the transmitted wavefront aberration, and the resistance on ejection process from the mold caused deformation of the surface.
- By controlling the V/P switchover and raising only the pressure peak in the mold, it was possible to improve the transcription ratio to some extent while suppressing deterioration of the transmitted wavefront aberration.
- However, its effect was smaller than in the case of increasing holding pressure. In order to obtain good transfer, it was necessary to apply pressure over a certain period of time.
- In this experiment, the transfer rate was about 40% while the transmitted wavefront aberration was kept low, and it was limited to about 50% even if neglected.

In order to further improve this problem, it is effective to reduce the resistance by grading or polishing the side surface, but they also may cause stray light and assembly error. Therefore, it is considered that a method of raising the surface temperature of the mold, such as heating cooling, is effective so that good transfer can be performed even at low pressure if possible.

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