Transcription Mechanism of Minute Surface Pattern in Injection Molding

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Abstract In injection molding of an optical disk, a toric lens, etc., their performance depends on the transcription preciseness of fine surface structure of a mold. However, transcription behavior has not been made clear yet, because transcription is made in very short time and the structure is very small. In this paper, transcription properties have been examined, by using V-grooves of various sizes, machined on mold surfaces, and the following results are obtained. (1) Transcription properties have been made clear experimentally and it was found that the mold temperature T_D makes great influence on the transcription property and that compression applying time t_c should be taken more than 2.0s for fine transcription. (2) A mechanical model of transcription process, in consideration with strain recovery due to viscoelastic property of polymer, is proposed. (3) Simulation results agree with experimental ones fairly well. It means that the transcription model is useful for estimation of transcription property in advance of an actual injection molding.

Keywords; Injection molding, Transcription property of fine surface structure, Transcription model, Viscoelastic property of polymer

1. Introduction

In injection molding of an optical element, such as an optical disk and a diffraction lens, the transcription property of fine surface structure affects the performance of it greatly. Transcription property can be improved by raising mold temperature, but it results cycle time increase. So prediction of the transcription property in advance of actual injection molding is very important for mold design. However, phenomenon in mold cavity is not easy to detect and since the structures to be transcribed is very small, the process of transcription mechanism has not been made clear yet.

Problems about fine structure transcription are divided into two categories: one is transcription of very fine but rather shallow pits or low indents, e.g. an optical disk, and the other is transcription of not so fine but rather deep grooves, e.g. a prism sheet for a liquid crystalline display.

There are not so many reports about transcription property in injection molding of fine surface pattern. Yoshii, et al. [1,2] discussed about the former case concerning to an optical disk in detail and proposed a mechanical model of transcription process of a groove by referring to bending deformation of an elastic beam. Yanagisawa [3] examined transcription property and clarified the conditions of mistranscription at ejecting stage. He suggested that the way of air blowing when disk is removed and the rigidity of mold and platens are important to obtain fine transcription. Ueda [4] examined the effect of polymer mechanical characteristics on transcription property in detail and suggested that the viscoelastic characteristic of the polymer near the glass transition temperature affects greatly. On the other hand, Kamiyama [5] reported about the transcription of deep grooves. He dealt with a prism sheet pattern experimentally. However, transcription mechanism has not been made clear yet and it is not easy to know the best transcription conditions.

In this research, transcription property of a very small V-groove on mold surface in wide range of injection molding conditions has been examined experimentally. Then, a simple transcription process model of a V-groove, in consideration with the deformation recovery of material after holding pressure releasing, is proposed. Finally, the results of the transcription height by using the proposed model are compared with experimental ones and it is proved that this simulation model is valid for the prediction of transcription state.

2. Experimental apparatus

In injection molding, holding pressure in a mold cavity and the applying time of it seems to affect transcription property greatly. So, a hydraulic cylinder is installed between platens of an injection molding machine. Injection molding condition can be changed easily by using this apparatus and detailed examination of transcription property becomes possible. Diameter of a disk to be molded is 120 mm. Thickness is 1.2 mm. A fine V-groove is machined by a sharp edged diamond cutter on the top surface of a cylindrical part and it is inserted in a mold plate (Fig. 1). Radius of the tool tip (r_c) is very small ($r_c < 1$ μm). V-groove angle is 90 ° . Size of V-groove width is changed in the range of 15 - 100 μm. Since the inserts are cylindrical, the direction of V-groove from that of a polymer flow can be set arbitrarily. Injection condition of mold temperature T_D, compression pressure P_c and , the melt flow velocity v are changed, further (Table 1). General-purpose Polystyrene (A&M STYRENE Co., Ltd.; Styron 679) and Polycarbonate (Teijin Chemicals Co, Ltd.; Panlight AD5503) are used as material.

A surface shape measuring microscope was used for measurement of the height of a formed projection (h_m) (see Fig.2).

3. Experimental results

3.1 Effect of mold temperature and injection rate on transcription property

Some experiments were carried out and it was found that transcription height h_m (height of V-shaped projection) increases greatly with increasing mold temperature T_D, where $T_D > T_g$ (T_g: glass transition temperature) and that it increases only a little with increasing melt flow velocity v.

3.2 Influence of V-grooves size and applied compression pressure

(a) Effect of V-groove size Transcription heights are examined in the situation that V-groove widths are 10, 30, 50 and 200 μm, or depths h_0= 5, 15, 25 and 100μm, and results are shown in Fig.3. The abscissa corresponds to the depth of a V-groove. The difference between experimental result and the straight dotted line in the figure shows the height of unfilled portion. It becomes approximately constant in the range of $h_0 > 25$μm, but it decreases with decreasing h_0 when h_0 is small. Effect of the directions of V-groove (θ) is small in comparison with that of V-groove size (refer to deference among three kinds of marks).

(b) Effect of applied compression pressure about two kinds of polymers Compression pressure P_c, compression holding time t_c, mold temperature T_D and V-groove size (depth) h_0 make large influence on transcription height, so these effects are examined. Results about PS are shown in Figs. 4 (a), (b), in which maximum values of the ordinates are set at the value of the depths of grooves (h_0). Effect of compression time t_c on transcription height h_m is shown in Fig.4(a). Here, open and solid marks correspond to the case of P_c = 30 and 60MPa. h_m decreases with decreasing t_c, when t_c < 2s. Such trend is observed in the other results, which will be shown below. When P_c is large, h_m increases a little, as is expected. In Fig. 4(b), where mold temperature T_D is set high (T_D=70℃), h_m increases considerably, comparatively to the result of Fig. 4(a) (T_D=60℃).

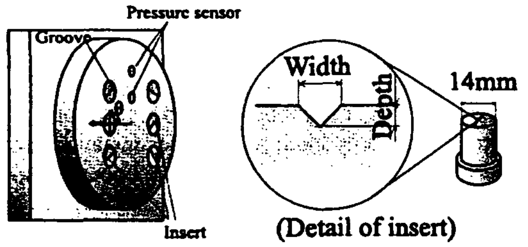


Fig.1 Mold and insert piece with V-groove

Table 1 Molding conditions

Polymer		polystyrene	polycarbonate
Polymer temp.	T_P(℃)	240	300
Mold temp.	T_D(℃)	60,70,80	100,120
Comp. applying time	t_C(s)	0.3～5.0	←
Comp. pressure	P_C(MPa)	30,60	←
Flow velocity	v(mm/s)	50～250	80
V-groove direction	θ(°)	0,45,90	←

Similar experiments are carried out about PC . Results are shown in Figs. 5 (a), (b). Transcription properties about P_c, t_c, T_D and h_0 are all very similar to those of PS. Especially, h_m also decreases with decreasing t_c when t_c < 2s, which was pointed out in Fig. 4 , already.

4. Measurement of viscosity and viscoelastic property of polymer

Viscosity of polymer is necessary in the analysis of transcription process. Since transcription phenomenon is deeply related with deformation until material solidifies, the viscosity data in low temperature, other than those obtained by a capillary rheometer, seems to be necessary for making a mechanical model of transcription process. Moreover, viscoelastic deformation recovery cannot be ignored in injection molding when compression pressure time is short. These material characteristics will be obtained in this chapter.

4.1 Measurement of viscosity

In the case of PS, the viscosity in high temperature range between 170 and 240℃ was measured by using a capillary rheometer. The viscosity in the range of 130-170℃ was measured by using a self-made shear tester. Furthermore, the viscosity in low temperature of 90-120℃ was done by using in-plane shearing deformation of a notched sheet specimen (Fig.6). Results are expressed by Eq. (1).

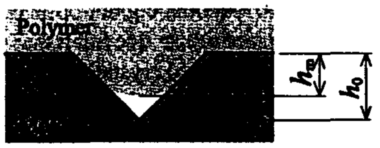


Fig.2 Transcription height h_m and V-groove depth h_0

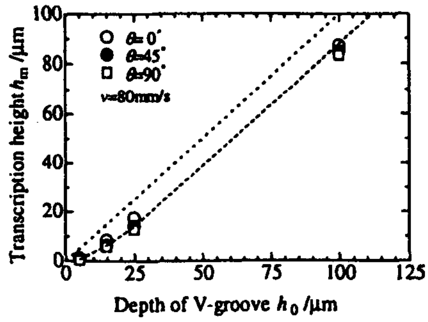
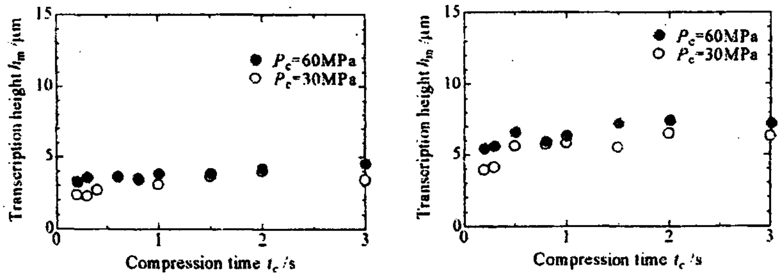
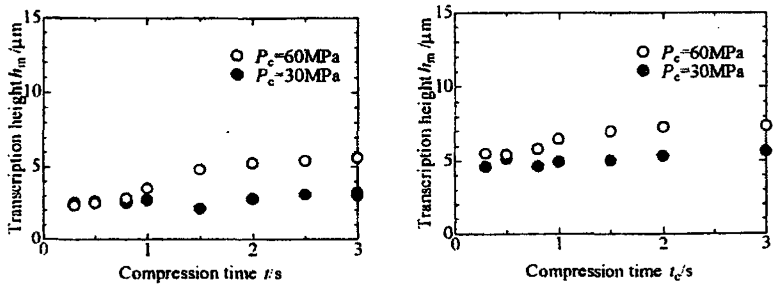


Fig.3 Effect of V-groove size (T_D=70℃, P_C=60MPa)



(a) T_D=60℃, h_0=15μm (b) T_D=70℃, h_0=15μm

Fig.4 Effect of compression time in the case of PS (v=80mm/s, θ=90°)



(a) T_D=100℃, h_0=15μm (b) T_D=120℃, h_0=15μm

Fig. 5 Effect of compression time in the case of PC (v=80mm/s, θ=90°)

$$\left.\begin{aligned} &\tau = 6.2\cdot10^{-7}\cdot\dot{\gamma}^{0.35}\exp(\frac{4500}{T+273})\ [\text{MPa}](134<T_p<240℃) \\ &\tau = 1.35\cdot10^{-24}\cdot\dot{\gamma}^{0.7}\exp(\frac{20720}{T+273})\ [\text{MPa}](90<T_p<134℃) \\ &\tau = 23\ [\text{MPa}]\ \ (T_p<90℃) \end{aligned}\right\}(1)$$

Each equation in Eqs. (1) stands on experimental results at $\dot{\gamma}$=6- 6080 s^{-1}, $\dot{\gamma}$=1- 30 s^{-1} and $\dot{\gamma}$=1- 30 s^{-1}, respectively.
As for PC, similar methods were applied and the following expressions are obtained.

$$\left.\begin{aligned} &\tau = 3.8\cdot10^{-11}\cdot\dot{\gamma}^{0.6}\exp(\frac{10000}{T+273})\ [\text{MPa}](184<T_p<300℃) \\ &\tau = 4.0\cdot10^{-18}\cdot\dot{\gamma}^{0.3}\exp(\frac{17500}{T+273})\ [\text{MPa}](135<T_p<184℃) \\ &\tau = 27\ [\text{MPa}]\ (T_p<135℃) \end{aligned}\right\}(2)$$

Each equation in Eqs. (2) stands on experimental results at $\dot{\gamma}$=6- 6080 s^{-1}, $\dot{\gamma}$=1- 30 s^{-1} and $\dot{\gamma}$=1- 30 s^{-1}, respectively.

4.2 Measurement of viscoelastic property

The in-plane shearing test (Fig. 6) was used again to measure the viscoelastic property of polymers. Some shear strain $\bar{\gamma}$ (say, 3.0) is applied to a specimen, which is heated in advance. After stress is removed, strain recovery is measured. In Fig. 7, three curves are shown, which correspond to the cases of loading shear strain rate $\dot{\bar{\gamma}}$ =1.2, 8.0 and 14.5s^{-1}, respectively. Material is PS. The peak of a curve corresponds to the end of loading and the curve after that point shows strain relaxation property. Loaded strain $\bar{\gamma}$ consists of recoverable strain γ_2^0 and permanent strain γ_1 (see Fig.7). γ_2^0 means " latent strain ", which is generated in material in loading stage. It is reserved in material if material is cooled immediately. In actual injection molding, some part of it is released without actualization and the other part remains in latent state.

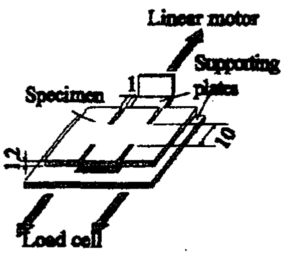


Fig.6 In-plane shear test specimen

Latent strain γ_2^0 in various loading conditions can be obtained from Fig.7 and similar other results. They are plotted in Fig. 8 and a fitting curve is obtained as follows.

$$\gamma_2^0 = 1.445\dot{\bar{\gamma}}^{0.20}\ \ (\bar{\gamma}=3.0) \qquad (3)$$

Effect of polymer temperature on the coefficient and the exponent in Eq. (3) was found to be small, so it is neglected. This equation can be available for 90 -140℃, because specimen melts at T_p=160℃ and because crazing occurs at T_p=90 ℃. It is assumed that γ_2^0 reduces linearly to zero, when T_p changes from 140℃ to 160℃.

Now, recovery characteristic equation will be obtained. The part of recovery process in a curve in Fig. 7 is replotted in logarithmic graph and the following equations are obtained.

$$\gamma_2 = \gamma_2^0 e^{-\frac{t}{a}},\ \frac{\dot{\gamma}_2}{\gamma_2} = -\frac{1}{a},\ a = 1.439\dot{\bar{\gamma}}^{-0.40} \qquad (4)$$

where $\gamma_2=\gamma-\gamma_1$ (see Fig. 7).
In actual injection molding, material is restrained in mold cavity during cooling time and latent strain is released to some extent. So supplemental experiments were carried out, where strain is restrained in some period (t_H) after loading. Strain recovery process is shown in Fig. 9. Results are summarized as follows.

$$\gamma_2^H = \gamma_2^0 e^{-\frac{t_H}{a_H}},\ \frac{\dot{\gamma}_2^H}{\gamma_2^H} = -\frac{1}{a_H},\ a_H = 11.37 \qquad (5)$$

Similar experiments are performed about PC and the following equations are obtained, which correspond to Eqs. (3) - (5), respectively

$$\gamma_2^0 = A\dot{\bar{\gamma}}^{0.12},\text{A}=0.35T_p+56\ (160\leqq T_p\leqq200℃)\ (6)$$

$$\gamma_2 = \gamma_2^0 e^{-\frac{t}{a}},\ \frac{\dot{\gamma}_2}{\gamma_2} = -\frac{1}{a},\ a = 0.578\dot{\bar{\gamma}}^{-0.04} \qquad (7)$$

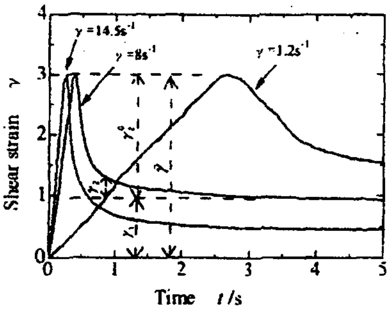


Fig. 7 Shearing and subsequent relaxation
(PS, T_p=120℃)

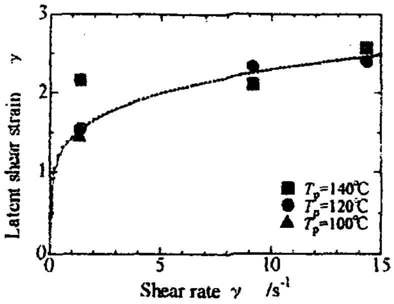


Fig. 8 γ_2^0 - $\dot{\gamma}$ curve
(PS, T_p=100~140℃)

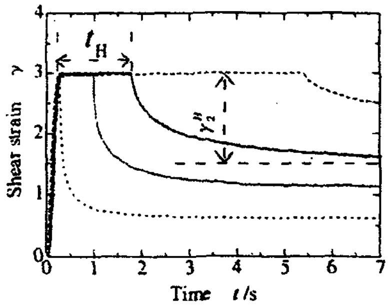


Fig. 9 Effect of constraint on strain relaxation
(PS, T_p=140℃)

$$\gamma_2^H = \gamma_2^0 e^{-\frac{t_H}{a_H}},\ \frac{\dot{\gamma}_2}{\gamma_2^H} = -\frac{1}{a_H},\ a_H = 6.67 \qquad (8)$$

5. Membrane model of transcription process

5.1 Deformation caused by compression pressure in transcription process

(a) Basic equations Polymer seems to pass over a V-groove in filling stage and to be swelled into the groove in packing and pressure holding stages. Then, it is assumed that transcription is achieved as follows: a cooled thin membrane of high viscosity is generated on the surface of material and it is bulged by packing and holding pressure. In this model, the following equation is obtained from equilibrium condition.

$$\int_0^d \sigma d\xi = \frac{R+R'}{2}\frac{p}{2} \qquad (9)$$

where p: pressure, σ: membrane stress, d: thickness of membrane, R, R' : membrane radius before and after time increment Δt)

Concerning membrane elongation Δl, Eqs. (10) and (10') are derived from geometrical relation in the cases before contacting of the membrane at V-groove surface and after contacting of it, respectively.

$$R'\theta' - R\theta = \frac{\Delta l}{2},\ R'\sin\theta' = R\sin\theta \qquad (10)$$

(θ: Fig. 10 (a), θ': θafter Δt)

$$\Delta a + (R' - R)\theta = \frac{\Delta l}{2} \qquad (a,\ \Delta a\text{: Fig. 10(b)}) \quad (10')$$

Here, membrane strain rate $\dot{\varepsilon}$ is

$$\dot{\varepsilon} = \frac{\Delta l}{l\Delta t} \qquad (11)$$

Relation between s and $\dot{\varepsilon}$ is given as Eq. (1), where relations $\sigma = \sqrt{3}\tau$ and $\dot{\varepsilon} = \dot{\gamma}/\sqrt{3}$ are assumed.

Thickness of a membrane d in the above discussions is assumed to correspond to the thickness of no flow layer, which is determined by simple Hele-Shaw flow analysis in considerations with thermal conduction [6]. It approximately coincides with the thickness of the layer, where material is cooled less than 160℃ in the case of PS and less than 200℃ in the case of PC, respectively.

Thermal constants, such as thermal conductivity and specific heat of material and a mold, λ_P λ_D C_P and C_D are referred to some handbook. Air layer between polymer membrane and mold surface is neglected. Then, λ_P and λ_D are altered by multiplying revision factor a and it is determined from one dimensional thermal conduction analysis is carried out for determination of d.

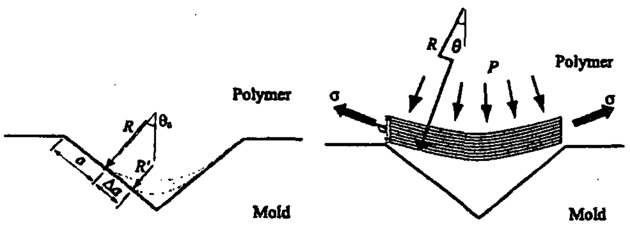
Analysis procedure is as follows: It is assumed that polymer cooling starts at the time when polymer pass over a V-groove (time $t = -t_0$). On the other hand, pressure increase starts at just filling time (t= 0), and pressure reaches the maximum value P_c at $t = t_1$. Unknown variables are R', θ, σ, ε or R', a, σ, ε. They can be solved by using Eqs. (9) (10), (10'), (11) and viscosity equations (1)-(6).

(b) Results t_1 is fixed at 0.15s by referring to experimental results. Solid lines in Figs. 11(a) and (b) show results of the cases of small V-groove (h_0=15μm), where T_D=60℃ and 70℃, respectively. P_c=60MPa. From these results, it was found that transcription height h_m almost converges to maximum at P_c=0.15s in every case. However, it does not agree with experiment one. This fact suggests that deformation recovery occurs after pressure releasing. Similar tendency is also observed in the cases of low pressure (P_c=30MPa; refer to dotted lines in Figs. 11(a) and (b)).

Results about PC are shown in Figs. 12(a), (b). In this material, T_g is high (T_g=145℃). So mold temperatures are set at high levels (T_D=100-120℃). Polymer temperature is also set high (T_P=300℃). Transcription property, obtained here, is approximately the same as that of PS. However, difference between numerical calculation results and experimental ones in short compression time (t_c < 2s) becomes larger, comparatively to that in PS.

5.2 Estimation of recovery of transcription height after pressure release

In 5.1, considerable difference between results of proposed model and experiment is observed. On the other hand, it was found that large strain recovery occurs in material testing results in 4.4. In this section, estimation of transcription height will be revised.



(a)Before contacting at V-groove surface (b)After contacting at V-groove surface

Fig. 10 Membrane model of transcription process

Let us assume that transcription material flow occurs in the following process:

i) Viscous deformation of a thin membrane occurs only in pressure increasing stage ($t < t_1$). Actually, deformation after that stage is quite little, according to the numerical results in 5.1, because material temperature decreases very rapidly.

ii) Latent strain, generated in the above viscous deformation stage, decreases to some extent during pressure holding stage. That strain change is not actualized.

iii) Residual latent strain causes deformation recovery after pressure release. This causes the reduction of transcription height.

Now deformation recovery in stages ii) and iii) will be estimated. A membrane is divided into many layers and recoverable strain in iii) is calculated by applying Eq. (6), in consideration with latent strain decrease in ii), with respect to each layer. Then, recoverable strain of each layer is summed up. Total shrinkage of membrane is calculated from this averaged strain and , further, transcription height decrease is estimated. Here, homogeneous reduction of height of a projected material is assumed.

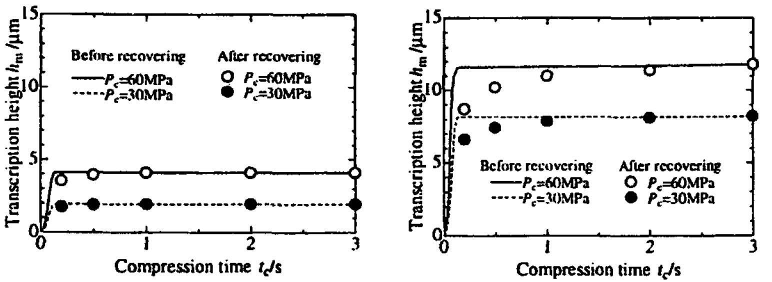
Transcription height after strain recovery about PS was calculated in the same condition as that, corresponding to each curve in Figs. 11(a), (b), and it was plotted by open and solid marks. From Figs. 11(a) and (b), it was found that transcription height decrease due to strain recovery become large in transcription of small grooves, when mold temperature T_D is high and pressure P_c is low. This tendency is remarkable in short pressure holding time t_c ($t_c < 2$s). These results approximately coincide with experimental ones (Fig.4). Detailed comparison will be made later.

About PC, similar analyses of strain recovery were made in the conditions, corresponding to the cases in Figs. 12(a), (b), and transcription height after strain recovery were plotted in the same figures. Effect of T_D, P_c and groove size on transcription height decrease is similar to that in the molding of PS, though it is a little bit stronger. This tendency is also observed in experimental results (see Figs. 4 and 5).

6. Comparison of simulation results with experimental ones

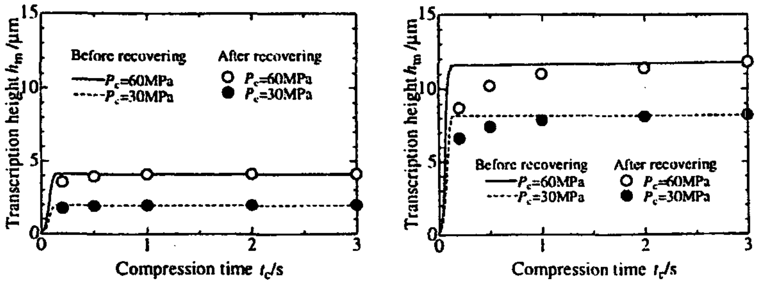
Experimental results of transcription height about PS (Fig. 4) and simulation results (Fig. 11) were compared and it was shown briefly that they coincide with each other. Similar conclusion was obtained about PC (Fig. 5 and Fig. 12). In this chapter, more exact comparison will be made.

Let us pay attention to the height of unfilled portion of a V-groove, or residual height. It depends on pressure holding time t_c. So, sufficiently long time for solidification of surface layer (t_c=3.0s) and rather short time (t_c=0.5s), in which large strain recovery occurs, are chosen as representatives. Correlation diagrams between simulation results and experimental ones at these times are obtained from Fig. 4 and Fig. 11 about PS and are shown in Figs. 13 (a) and (b), respectively. It was found that the correlations is rather well in general . It should be noticed that the correlation in the simulation of short pressure holding time (Fig. 13 (b)) is greatly revised by introducing the transcription height reduction due to strain recovery. The amounts of this correction can be known from results at t_c=0.5s in Figs.11 (a),(b). In the case of a large groove and high mold temperature (open circle and open triangular marks), simulation results become a little bit smaller; comparatively with experiments. That error may possibly be caused by due to the assumption of over high heat current resistance between polymer and a mold in the analysis of strain recovery , though exact discussions cannot be made in this paper.



(a) T_D=100℃, h_0=15μm (b) T_D=120℃, h_0=15μm

Fig. 11 Simulation results of transcription height h_m in the case of using PS



(a) T_D=100℃, h_0=15μm (b) T_D=120℃, h_0=15μm

Fig. 12 Simulation results of transcription height h_m in the case of using PC

Similar correlation diagrams about PC at t_c=3.0s and 0.5s are shown in Figs. 14(a) and (b), respectively. It was proved that the correlation is also rather well.

Consequently, it is concluded that the simulation of transcription height by the use of a membrane bulging model is useful for a brief estimation of transcription height of various size groove in various injection molding conditions and that the correction of the transcription height reduction due to strain recovery is important in the simulation. This simulation can be extended to the estimation of unfilled portion size of a minute groove corner on a mold in injection molding in various conditions.

7. Conclusions

Transcription property of V-grooves in various sizes have been investigated experimentally and a transcription process model is proposed. Results are as follows:

(1) From experiments, it was found that transcription height h_m, i. e., height of the projection flowed in a V-groove, increases with increasing mold temperature T_D and with increasing pressure holding time t_c and that h_m saturates to the limiting value around t_c=2s.

(2) A membrane bulging model of transcription process, analysis in consideration with a strain recovery due to the viscoelastic property of polymer, is proposed.

(3) Simulation results agree well with the experimental ones. It means that the transcription model is useful for the prediction of transcription property before actual injection molding.

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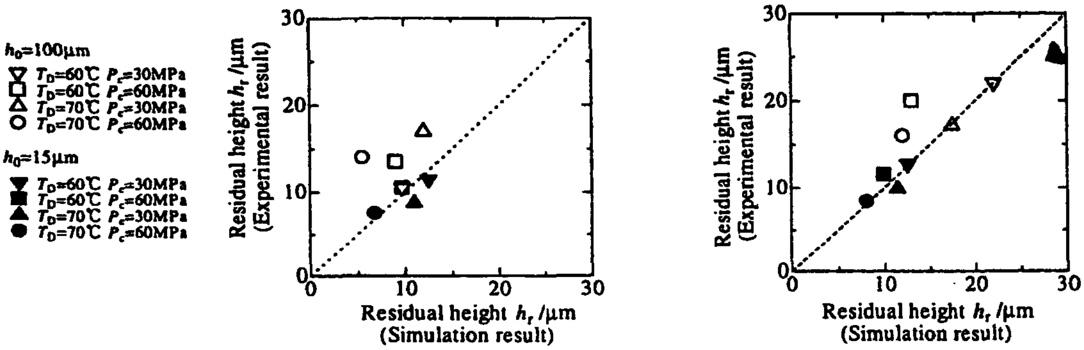
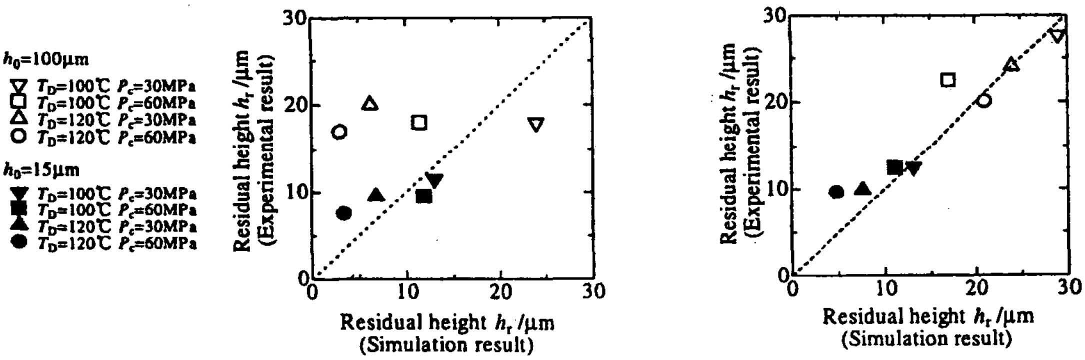


(a) t_c=3s (b) t_c=0.5s

Fig.13 Comparison of simulation and experiment about height of unfilled portion (or residual height) (PS)



(a) t_c=3s (b) t_c=0.5s

Fig.14 Comparison of simulation and experiment about height of unfilled portion (or residual height) (PC)