# **Injection Molding of a Diffractive Optical Element**

# Terje Tofteberg, Hélène Amédro, Erik Andreassen

SINTEF Materials and Chemistry, Oslo, Norway

The injection molding of a microfeatured component, a diffractive optical element, was studied. The component has a wave-like pattern on the surface, with amplitude 0.5  $\mu$ m and wavelength 3  $\mu$ m. Two different polymers were used: a polymethylmethacrylate and an ethylene-norbornene copolymer (cyclic olefin copolymer). The topography was investigated using white light interferometry (WLI), atomic force microscopy (AFM), and scanning electron microscopy (SEM). A new WLI-based technique is proposed for rapid quantification of the replication of periodic surface patterns. This technique gives almost the same information regarding the degree of replication as AFM but can be performed much faster. Quantitative data on the degree of replication as function of processing conditions are presented. At optimal conditions, almost perfect replication is obtained using both materials. At suboptimal conditions, it is observed that the degree of replication increases with increasing injection velocity and increasing mold temperature, with similar characteristics for both materials. The difference in replication quality between the two materials seems to be related to the different temperature dependencies of the viscosities. POLYM. ENG. SCI., 48:2134-2142, 2008. © 2008 Society of Plastics Engineers

# INTRODUCTION

In his visionary talk "There's plenty of room at the bottom" given in 1959 at Caltech, Richard Feynman suggested plastic materials as ideal candidates for rapid replication of parts with micro- and nanosized features [1]. Today, such parts are mass produced using different technologies, and the most common are injection molding and hot embossing.

Our research addresses challenges regarding the use of polymer materials in injection-molded, high-precision components. The focus is on components with the largest outer dimension in the centimeter range, but with features (channels, gratings, etc.) in the micrometer range. We refer to these as microfeatured components.

This study is based on molding trials with a diffractive optical element (DOE). The DOE design was described

by Løvhaugen et al. [2]. It is an essential part of a lowcost infrared spectrometer, which for example, can be used to identify different types of polymers. The molded DOE works in reflection and it is sputtered with a thin gold layer after molding to have the required reflectance.

Other products with micrometer and submicrometer sized features fabricated using injection molding include optical storage media such as the CD, the DVD, and the Blu-ray Disc, where the accurate replication of microfeatures using injection-compression molding is essential for the product quality. The physical properties of a surface can also be altered dramatically by shaping it on the microscale, for instance, to produce superhydrophopic surfaces [3].

No limit has yet been set, as to how small features that can be replicated using injection molding. Fibrillar structures with details down to 10 nm [4] were replicated by injection molding, as well as characteristic wave patterns from deep reactive ion etching with features down to 5 nm [5]. However, both these structures had very low aspect ratios ( $\ll$ 1). For some submicrometer structures, it has been suggested that the adhesive energy between the polymer and the mold (insert) may be an important factor for the replication [6].

Several authors have reported that increasing mold temperature and injection velocity improves the replication of microfeatures [6–14]. However, only limited quantitative data exists on how the mold temperature and the injection velocity influence replication. On the other hand, too high mold temperatures can damage microfeatures [15], high mold temperatures will increase the cycle time [16], high injection velocity may lead to poor surface quality [17], and the injection velocity is limited by the injection molding machine. This makes it important to obtain quantitative data, linking process parameters with replication quality, in order to optimize the injection molding of parts with microfeatures.

Other process parameters do also affect the replication. It has been demonstrated that higher melt temperature [7, 17, 18] and higher holding pressure [7, 18] can have a positive effect. There is also a coupling between process and geometry including microfeatures. Some examples: the effect of holding pressure increases with increasing cavity thickness [7]. Grooves parallel to the flow direction are easier to replicate than those perpendicular to the flow

*Correspondence to*: Terje Tofteberg; e-mail: terje.tofteberg@sintef.no Contract grant sponsor: Research Council of Norway.

DOI 10.1002/pen.21154

Published online in Wiley InterScience (www.interscience.wiley.com). © 2008 Society of Plastics Engineers



FIG. 1. A drawing of an injection-molded part with some dimensions indicated in millimeters. The microfeatures are in the central square area (10 mm  $\times$  10 mm). A combined pressure and temperature sensor is mounted in the mold half opposite the Ni shim, in the position marked with a dark gray circle (just in front of the square with microfeatures).

[7, 18, 19]. Features near the gate may [7, 20] or may not [17] be easier to replicate, e.g. depending on the aspect ratio of the microfeatures. Flow instabilities that reduce the replication quality of certain microfeatures occur at certain processing conditions [6, 21].

Special techniques and equipment can be used to improve the quality of injection molded microfeatured parts (microsized parts is not the topic of this study). Variotherm processing (variation of the mold temperature through the cycle), evacuation of the air inside the cavity prior to injection, and injection-compression molding are the most common techniques. Several groups have developed and studied variotherm processes. In these processes the cavity surface is heated, prior to injection to enhance the replication, and then cooled in order for the polymer to reach the ejection temperature. For amorphous polymers, the cavity surface is typically heated to temperatures above the glass transition temperature. The cavity surface can be heated from the interior of the mold (by circulating liquids or electrical heating) or from the surface. A smaller mass is heated with the latter techniques, giving shorter cycle times. Implementations of surface heating include induction heating [22], proximity effect heating [23], and infrared heating. Positive effects on product quality have also been reported with cavity evacuation [7, 9, 19] and injection-compression molding [24].

In the present study, conventional injection-molding equipment was used. The effect of mold temperature and injection velocity on the replication quality is studied.

# **EXPERIMENTAL**

# Part Geometry and Mold Insert

The geometry of the injection molded part can be seen in Fig. 1. The area with microfeatures was  $10 \text{ mm} \times 10 \text{ mm}$ . A microstructured mold insert was clamped in a modular base mold. The mold insert was a 0.3-mm-thick Ni shim made by electroplating a resist structured by electron beam lithography [2]. The surface topography of the shim was an irregular wave pattern with wave height  $\sim$ 500 nm and wavelength 3  $\mu$ m.

# Polymers

Two different amorphous materials were used in the injection molding trials. Both of them had a good ability to replicate microstructures, according to the manufacturers. The materials were a polymethylmethacrylate (PMMA; Plexiglas POQ62 from Evonik Röhm) and an ethylene-norbornene copolymer, often referred to as a cyclic olefin copolymer (COC; Topas 5013S-04 from Topas Advanced Polymers). The latter had about 50 mol% norbornene [25]. The glass transition temperatures are given in Table 1.

# Injection Molding

The injection molding was performed on a servoelectric Battenfeld EM 50/120 machine with maximum clamping force 500 kN and screw diameter 25 mm. The injection velocity and the mold temperature were varied. All other molding parameters were kept constant. An overview of the parameters used is shown in Table 1. Note that in this article, injection velocity is defined as the flow front velocity given as the volume flow divided by the cross sectional area where the microfeatures are located. It has been shown that, at high injection rates, the relationship between volume flow (cm<sup>3</sup>/s) and flow front velocity (mm/s) is not completely linear [9], probably because of compression effects. This possible effect is not included when specifying the flow front velocity. Also note that both polymers were molded with a melt

| TABLE 1.    Materials and processing parameters. |                 |                  |                                 |   |                                 |                           |
|--|-----------------|------------------|---------------------------------|---|---------------------------------|---------------------------|
| Grade  | Polymer<br>type | $T_g^{\ a}$ (°C) | Mold<br>temp. <sup>b</sup> (°C) | Injection<br>velocity <sup>c</sup> (mm/s) | Melt<br>temp. <sup>d</sup> (°C) | Holding<br>pressure (MPa) |
| Plexiglas POQ62<br>Topas 5013S-04                | PMMA<br>COC     | 99.6<br>130.0    | 40–80<br>60–125                 | 130–1200<br>130–1300                      | 240<br>270                      | 60<br>50                  |

<sup>a</sup> Glass transition temperature measured using DSC at heating rate  $10^{\circ}$ C/min. Sample first heated to above  $T_{e}$ , cooled down, and then heated again.  $^{b}$  Recommended mold temperatures: 60–90°C (the PMMA) and 95–125°C (the COC).

<sup>c</sup> This is the melt front speed through the cross-section with microfeatures, i.e. volume flow divided by cross-sectional area.

<sup>d</sup> The temperature set for the last cylinder element and the nozzle, confirmed by measurements in the barrel end cap (using a Kistler 4083A sensor).

temperature 140 K above their respective glass transition temperatures.

The volume flow was kept constant during injection, and the switchover to holding pressure was set to occur when a specified volume had been injected. This nominal switchover volume was the same for all trials within one polymer series. It should be noted, however, that there is a certain retardation time involved for the injection velocity to reach zero. At the highest injection velocities, the extra volume filled during this retardation time is not insignificant. Hence, for high injection velocities, the real switchover volume is higher than the nominal value, and it increases with increasing injection velocity.

For each change of injection velocity, five shots were made before taking the sixth as characteristic for that setting. For one setting using PMMA, the degree of replication was measured for shots 6–15, and it was seen that the replication varied only slightly and no trend was observed. More details can be found in the Results section.

The mold temperature was controlled using circulating water at a constant temperature, and the mold temperatures reported later refer to the set water temperature. A combined temperature and pressure sensor (Kistler 6190BA) located in the mold surface opposite to the microfeatures confirmed that this was also close  $(\pm 2^{\circ}C)$  to the surface temperature when the melt was injected. Some temperatures that were significantly outside the recommended settings were tested, in order to check how this influenced the replication of the microfeatures. When changing the water temperature, the mold temperature was allowed to stabilize, so that the maximum and minimum temperature of the mold within a cycle did not change from cycle to cycle.

# Characterization of Molded Parts Using AFM, SEM, and WLI

The surface topographies of parts and of the Ni shim were characterized by atomic force microscopy (AFM), scanning electron microscopy (SEM), and white-light interferometry (WLI).

AFM was performed in tapping mode. The instrument was a Dimension 3100 from Digital Instruments. A tetrahedral tip (DP14/GP/AIBS from MicroMasch) was used. The same peak near the middle of the microfeatured area was investigated on molded parts and on the shim.

The SEM instrument was a Quanta 600 FEG from FEI Company. Before the parts were investigated by SEM, a 50-nm-thick gold layer was sputtered on the surface.

The WLI instrument was a WYKO NT-2000 from Veeco Instruments. To measure the replication quality,  $45 \ \mu m \times 60 \ \mu m$  images near the center of the microfeatured area were recorded. The parts were manually aligned, so that the pictures were taken from almost the same location ( $\pm 3 \ \mu m$ ) for all parts. WLI is a coarser method than AFM, and the lateral resolution depends

on the microscope used. In our case, the resolution was 0.5  $\mu$ m in the plane and 10 nm in the vertical direction. WLI can however, as will be shown, be used to estimate the degree of replication within the same accuracy as AFM. We do this by not only considering a single peak in the topography, but also doing a Fourier transform of the entire image. Details are given in the next section.

## Degree of Replication From WLI Measurements

The topography of a DOE can be described by a function h = f(x,y) which gives the height h as a function of the spatial coordinates x and y. We first assume that the topography is periodic, where we have aligned the coordinate axes so that there exists a P for which f(x,y + P) =f(x,y) for all x and y. The power spectral density (PSD)  $\Phi(\omega,x)$  of such a continuous function taken in the y-direction is given along any line parallel to the y-axis as

$$\Phi(\omega, x) = \left| \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} f(x, y) e^{-i\omega y} \, dy \right|^2 = \frac{F(\omega, x) F^*(\omega, x)}{2\pi},$$
(1)

where  $F(\omega,x)$  is the Fourier transform of f(x,y) and  $F^*(\omega,x)$  is its complex conjugate. For an electromagnetic or acoustic wave,  $\Phi(\omega,x)$  is proportional to the amount of energy carried by given frequencies, therefore, the prefix power. For a 2D periodic pattern, the PSD gives information about the strength of the signal at the given frequency. Before discussing the difficulties coming from the fact that our signal is finite, discrete, and not perfectly periodic, we show how the degree of replication could be defined in the ideal case.

Figure 2 shows how the PSD transformation works on a periodic saw-tooth signal. The first observation to be made is that the largest peak is located at the inverse of the characteristic wavelength of the saw-tooth pattern. This is clearly seen when restoring the signal using the inverse Fourier transform of the truncated spectrum. The next peaks are located at integer multiples of this frequency and corresponds to the coefficients of the Fourier series of the saw-tooth signal. We define the degree of replication  $\alpha$  as

$$\alpha = \frac{\sqrt{I_{\text{DOE}}}}{\sqrt{I_{\text{shim}}}},\tag{2}$$

where *I* is the integral of the largest peak in  $\Phi(\omega, x)$ . This integral is proportional to the square of the amplitude of the signal in Fig. 3.

In our case, the topography is measured by WLI as a discrete signal of finite extension. To be able to define the PSD from Eq. 1, the discrete version of the Fourier transform must be used. There is also a challenge in the fact that the topography is not completely periodic. An exam-



FIG. 2. An illustration of the PSD function. (a) Original saw-tooth signal, (b) PSD of the saw-tooth signal, (c) truncated spectrum used for calculating the degree of replication, (d) restored signal based on the truncated PSD.

ple of the topography as measured by WLI is shown in Fig. 3. Since not all lines parallel to the *y*-axis are equal, we found it most useful to define the PSD as an average over all *x*-values.

There are some advantages with this method compared to using AFM and comparing the structures on the molded part with the corresponding (but negative) structures on the Ni shim. The PSD from WLI includes statistical information representing an area, and all the information is used to define the degree of replication. Hence, this method gives a better statistical average for the degree of replication than AFM studies, where only a few peaks/profiles are analyzed. In addition, the WLI measure-



FIG. 3. Topography by WLI for a molded PMMA DOE.

ments are fast, typically on the order of a second, once the alignment and focusing is done, compared to the relatively slow AFM that needs to scan the surface pixel by pixel.

However, a scalar variable is not able to capture the full complexity of a surface, neither is the typical resolution of WLI good enough to capture as fine details as AFM. Still the WLI/PSD method allows for rapid and adequate analysis of a large number of parts.

# RESULTS

#### Degree of Replication Versus Processing Conditions

A high degree of replication was obtained with the PMMA, with mold temperatures in the interval recommended by the manufacturer, i.e. 60–90°C. Figure 4 shows how the replication improves when increasing the injection velocity and the mold temperature. These results indicate that the processing window, giving good replication, is quite broad. Hence, there is some freedom to



FIG. 4. The degree of replication as measured using WLI/PSD for PMMA DOEs as function of mold temperature and flow front velocity. The lines are guides for the eyes. With a mold temperature of  $80^{\circ}$ C and a flow front velocity of 900 mm/s, 10 consecutively molded samples were analyzed, see main text for details.



FIG. 5. The degree of replication for COC DOEs as a function of mold temperature and flow front velocity. The lines are guides for the eyes.

change processing conditions to meet other criteria. Also with the COC it was possible to achieve a high degree of replication, but as can be seen in Fig. 5, the mold temperature had to be set to the maximum of the recommended range.

When comparing the two polymers regarding the effect of mold temperature on replication there are two main observations. (1) For high mold temperatures (near  $T_g$ ), the PMMA gives better replication than the COC for a given difference between mold temperature and  $T_g$ . (2) The effect of mold temperature on replication is higher for the PMMA than for the COC. Note that both Fig. 4 and Fig. 5 contain data for the mold temperatures ( $T_g$  – 20 K), ( $T_g$  – 40 K), and ( $T_g$  – 60 K).

When the surface of the polymer solidifies it can be in contact with the Ni shim or not, and the resulting surface textures are different, as shown in the SEM picture in Fig. 6.



FIG. 6. SEM picture of a molded COC DOE. Three periods of the diffractive grating are seen. The degree of replication (from WLI) is 0.72. On the top of the ridges (white arrow), where the polymer was not in contact with the Ni shim when solidifying, the texture appears different.



FIG. 7. AFM data for the same peak on different injection-molded PMMA parts, and on the Ni shim (inverted data). The numbers in the legend refer to the degree of replication determined by the WLI/PSD method.

# Verification of the Degree of Replication Obtained With the WLI Method

The degree of replication obtained with the WLI/PSD method was compared with AFM data for one specific wave. As shown in Fig. 7, the degree of replication obtained with WLI/PSD correlates well with the peak height measured with AFM, justifying the use of the WLI/PSD method to quantify the degree of replication. The fact that the given degree of replication varies smoothly with the processing parameters, as shown in the previous section, also speaks for its validity.

Since the WLI measurements were based on manual alignment of the sample, all measurements were not taken at the exact same location on the DOE. To see how this influenced the results, one PMMA part was manually aligned and analyzed 10 times. These 10 values for the degree of replication had a standard deviation of 1.7%. For comparison, 10 consecutively molded PMMA parts (same molding parameters) were analyzed. The standard deviation of the degree of replication values from these 10 trials was 1.9%. Note that the difference between consecutively molded parts is not significantly larger than the uncertainty of the measurements.

# DISCUSSION

The degree of replication increases with increasing mold temperature and injection velocity for the two polymers in this study. The replication of the microfeatures can only take place as long as the polymer has sufficient fluidity.

#### How the Mold Temperature Influences the Replication

A high mold temperature will increase the degree of replication by keeping the polymer at a sufficiently low



FIG. 8. Log-log plot of zero shear rate viscosity as function of temperature. Both polymers were injected with a melt temperature of  $(T_g + 140)^{\circ}$ C (Table 1) and thus had similar viscosities. The slope *n* is defined from  $\log \eta = n \log(T - T_g) + \log b$ .

viscosity for a longer time. The magnitude of this effect depends on how fast heat is transferred from the hot polymer to the mold wall. The most common way to describe this heat transfer is to use a heat-transfer coefficient, saying that the heat flow is proportional to the temperature difference between the polymer and the wall. In a numerical simulation, the degree of replication of microfeatures will generally depend significantly on the value chosen for the heat-transfer coefficient; see e.g. Ref. [12]. Still there is no consensus regarding which value to use, and experimental evidence suggests that the value changes during the injection-molding cycle [26].

How much the polymer properties change with temperature will also be important for how the mold temperature influences replication. Figure 8 shows viscosity at zero shear rate versus temperature for the two polymers, based on Cross-WLF data from the Moldflow database [27]. The temperature dependence of the viscosity is stronger for the PMMA than for the COC. The difference between the two materials depends on the shear rate and becomes small above  $\sim 100 \text{ s}^{-1}$ . However, the deformation rates can be low during the filling of the last remaining volume of the microfeatures, as the pressure builds up after the melt front has passed (discussed in the next section).

The observation that the PMMA gives better replication than the COC at high mold temperatures (relative to the respective glass transitions) could be due to its lower viscosity at high temperatures and low shear rates. The zero shear viscosity curves in Fig. 8 cross at  $(T - T_g) \sim$ 130 K. The crossing point moves to higher temperatures with increasing shear rate. At a shear rate of 10 s<sup>-1</sup>, the curves cross above  $(T - T_g) = 140$  K, which is the melt temperature in the molding trials. However, with high mold temperatures, the lower PMMA viscosity at low rates and high polymer temperatures could account for the higher degree of replication with this polymer compared to the COC. Shear heating could also contribute to the temperature being above the crossing point. It should, however, be noted that capillary rheometry data at low shear rates, and the extrapolation to zero shear rates, are uncertain. Further work is planned to characterize the rheology of these polymers, including the behavior near the glass transition and the effective no-flow temperature.

The observation that the effect of mold temperature on replication is higher for the PMMA than for the COC could be explained by the viscosity curves in Fig. 8. Our hypothesis is that the change in replication when changing the mold temperature is related to the temperature dependence of the viscosity. The PMMA has a steeper curve in Fig. 8. Hence, a given reduction in mold temperature will result in a larger viscosity increase for this polymer than for the COC.

Other thermal properties of the polymers may also affect the replication. The basic thermal parameters are thermal conductivity, specific heat capacity, and density. The PMMA in this study has higher specific heat capacity and density than the COC, also if the values are compared at a certain temperature above the respective glass transitions. The values for the thermal conductivity are not so clear. The two polymers have roughly the same conductivities in the Moldflow database. Other published values vary substantially for given polymer types or grades, probably because of different measurement techniques and experimental uncertainty.

The thermal diffusivity, i.e., the ratio of thermal conductivity to the product of specific heat capacity and density, is important in the injection-molding process. The thickness of the solidified layer is often found to be proportional to the square root of the thermal diffusivity. In our study, the PMMA has lower thermal diffusivity than the COC. This could contribute to the good replication with the PMMA at high mold temperature, but cannot explain why the replication with PMMA is more sensitive to mold temperature, at least not without taking into account the variation of the thermal diffusivity with temperature. For the replication of microfeatures, the heattransfer coefficient (or other entities describing local effects near the boundary) seems to be more important than the thermal diffusivity. Yoshii et al. [20] found no correlation between thermal diffusivity and degree of replication for four amorphous polymers.

The thermal effusivity, i.e., the square root of the product of thermal conductivity, specific heat capacity, and density, determines, in an idealized case, the contact temperature between the polymer and the mold (shim) [20]. The PMMA has somewhat higher thermal effusivity than the COC, but the Ni shim has a thermal effusivity that is about 30 times larger than the effusivities of the polymers. This leads to a contact temperature that for both polymers is less than 10 K above the mold temperature and that is about 0.8 K higher for the PMMA than for the COC. Again, this cannot explain why the replication with the PMMA is more sensitive to mold temperature, at least not without taking into account the variation of the thermal efffusivity with temperature.

# How the Injection Velocity Influences the Replication

The injection velocity may influence the replication via several different effects. (a) Faster injection means less cooling of the polymer before reaching the mold wall. (b) Faster injection will give more shear heating. (c) Faster injection will cause a viscosity reduction due to shear thinning. (d) Faster injection will cause a higher pressure and faster pressure buildup at the wall, which will enhance the flow into the microfeatures. (e) The magnitude of the injection velocity may affect the heat transfer to the mold (the heat-transfer coefficient). (f) When switching from velocity control to pressure control, the effective switchover volume and associated pressure may increase with increasing injection velocity because of the retardation time of the injection unit. Some of these effects will be discussed below.

The pressure effect will be considered first. Faster injection will cause a higher pressure and faster pressure buildup at the wall. For a Newtonian fluid injected between two parallel plates, the pressure field behind the flow front has been solved analytically [28]. The pressure at the wall at a given distance behind the flow front is proportional to the injection velocity. The pressure also depends linearly on the distance from the flow front, except for the fountain flow region at the flow front. The net effect of this is that the pressure as a function of time is proportional to the square of the injection velocity for a Newtonian fluid. However, a polymer melt is highly shear thinning and thus not Newtonian. Shear thinning and shear heating will cause the polymer to flow more easily when injected at a high velocity, and thus partly cancel the effect the velocity has on the pressure building up at the wall.

The filling of the part in Fig. 1 without microfeatures was simulated with Moldflow [27] in the Hele-Shaw framework (planar flow). The heat-transfer coefficient at the wall was set to 5000 W/( $m^2$  K), but changing it did not influence the results presented here. Simulated pressure vs. time at the wall near the microfeatures agrees well with measurements, as shown in Fig. 9, although the pressure is overpredicted for the PMMA. These results indicate that the effect the injection velocity has on the pressure can be described well using a generalized Newtonian model for the viscosity of the polymer.

A high injection velocity will cause shear thinning and shear heating. These effects will enhance the flow into the microfeatures. The maximum temperature during the injection molding cycle, as measured with the thermocouple flush with the mold wall, was around 3 K higher when injecting the melt at 1300 mm/s than when injecting at 200 mm/s. The details of the rheology on this size scale are not completely understood, and it is suggested that viscoelastic effects can be important for the flow into microfeatures [6].



FIG. 9. Measured (symbols) and simulated (lines) cavity pressure vs. time. The location of the pressure sensor is indicated in Fig. 1. The diagrams show results for COC with mold temperature  $110^{\circ}$ C (a) and PMMA with mold temperature  $70^{\circ}$ C (b).

The injection velocity may also influence the heattransfer coefficient. Xu et al. [12] claimed good agreement between simulated and experimental replication of microfeatures when using a heat-transfer coefficient varying via the local Nusselt number.

It could also be argued that at high velocities the polymer carries more momentum as it approaches the wall and thus has a higher capability for filling the microfeatures. However, since the Reynolds number for the polymer melt is so low (typically <1 in regular injection molding and much lower when using a characteristic length of around 1  $\mu$ m), this effect will not be of any importance.

# Empirical Relationship Between Process Parameters and Degree of Replication

As shown in Fig. 10, a good correlation exists between the degree of replication and the following expression:

$$\frac{V_{\rm inj}^2}{\left(\frac{T_{\rm g} - T_{\rm mold}}{\Delta T}\right)^n}.$$
(3)



FIG. 10. The degree of replication for both materials and different molding conditions plotted as function of the empirical expression from Eq. 3. See main text for details.

Here  $v_{inj}$  (m/s) is the velocity of the flow front during injection,  $T_g$  (K) is the glass transition temperature of the polymer,  $T_{mold}$  (K) is the mold temperature, n (-) is the absolute value of the slope in Fig. 8, and  $\Delta T$  is a scaling factor which was chosen to be 60 K to make the data for the two materials overlap. Note that this is only an empirical parameter.

*Eq.* 3 represents the ratio between the driving force that forces the polymer into the microfeatures and the resistance to flow.

The driving force is the pressure building up in the cavity after the flow front has passed the microfeatures. It will depend on the viscosity of the melt, the geometry of the cavity, and the injection velocity. In this case, the geometry is kept fixed, and as shown in Fig. 8, the zero shear rate viscosities of the two polymers are similar at the injection temperature, meaning that even though these effects will clearly influence the replication, they will enter the expression mentioned earlier as a constant term. It was also observed in both experiments and the Moldflow simulations that the mold temperature only had a marginal influence on the cavity pressure. The only parameter that is varied and which influences the cavity pressure is the flow front velocity. It will influence the viscosity through the shear rate and, given a constant viscosity, will cause the pressure to increase proportional to  $v_{ini}$  squared.

The resistance to flow into the microfeatures depends on the geometry of the microfeatures and the viscosity of the polymer in the microfeatures. Once again, the geometry is kept fixed and will enter as a constant term. For simplicity we have chosen to assume that the shear thinning effect in the microfeatures (easier flow) will cancel out the effect of the shear thinning in the main geometry (lower pressure).

The characteristic temperature in the microfeatures will decrease rapidly from the melt temperature down to the mold temperature. The temperature decrease will depend on the heat-transfer coefficient, the thermal diffusivity, and the contact temperature (thermal effusivity). If we neglect the differences between the polymers regarding thermal diffusivity and effusivity, and assume that the heat-transfer coefficients will be similar for the two polymers, we can express the characteristic temperature in the microfeatures as the difference between the mold temperature and the glass transition temperature to the power of n, similar to how the zero shear rate viscosity varies with temperature as

$$\eta_{\rm o} = b \left( T - T_{\rm g} \right)^n,\tag{4}$$

as seen in Fig. 8.

Even though a simple scalar expression never will be able to concentrate all information from the physically complex injection molding process, the expression given in Eq. 3 can provide useful information when predicting and optimizing the injection-molding process.

#### CONCLUSION

We have described a fast and accurate method for determining the degree of replication of parts with periodic microfeatures. This method made it possible to study a large number of injection-molded parts and, from the data acquired, to present an empirical expression relating the degree of replication to the variation in injection velocity and mold temperature.

# ACKNOWLEDGMENTS

We thank Odd Løvhaugen at SINTEF ICT for providing the Ni shim.

# REFERENCES

- 1. R.P. Feynman, Eng. Sci., 23, 22 (1960).
- O. Løvhaugen, I.-R. Johansen, K.A.H. Bakke, B.G. Fismen, and B.G. Nicolas, J. Mod. Opt., 51, 2203 (2004).
- E. Puukilainen, T. Rasilainen, M. Suvanto, and T.A. Pakkanen, *Langmuir*, 23, 7263 (2007).
- N. Gadegaard, S. Mosler, and N.B. Larsen, *Macromol. Mater. Eng.*, 288, 76 (2003).
- A.K. Angelov and J.P. Coulter, in *Proceedings of SPE* ANTEC, Cincinnati, OH, 2987 (2007).
- H. Pranov, H.K. Rasmussen, N.B. Larsen, and N. Gadegaard, *Polym. Eng. Sci.*, 46, 160 (2006).
- 7. X. Han, H. Yokoi, and T. Takahashi, *Int. Polym. Process.*, **21**, 473 (2006).
- 8. X. Han and H. Yokoi, Polym. Eng. Sci., 46, 1590 (2006).
- H. Yokoi, X. Han, T. Takahashi, and W.K. Kim, *Polym. Eng. Sci.*, 46, 1140 (2006).
- 10. N.S. Ong, H.L. Zhang, and W.H. Woo, *Mater. Manuf. Process.*, **21**, 824 (2006).
- 11. Y.-C. Su, J. Shah, and L. Lin, J. Micromech. Microeng., 14, 415 (2004).

- 12. G. Xu, L. Yu, L.J. Lee, and K.W. Koelling, *Polym. Eng. Sci.*, **45**, 866 (2005).
- J. Zhao, R.H. Mayes, G. Chen, P.S. Chan, and Z.J. Xiong, *Plast. Rubber Compos.*, **32**, 240 (2003).
- 14. R. Wimberger-Friedl, J. Inj. Mold. Technol., 4, 78 (2000).
- M.J. Madou, Fundamentals of Microfabrication: The Science of Miniaturization, CRC Press, Boca Raton, FL, USA (2002).
- M. Heckele and W.K. Schomburg, J. Micromech. Microeng., 14, 1 (2004).
- B. Sha, S. Dimov, C. Griffiths, and M.S. Packianather, J. Mater. Process. Technol., 183, 284 (2007).
- K. Mönkkönen, J. Hietala, P. Paakkonen, E.J. Paakkonen, T. Kaikuranta, T.T. Pakkanen, and T. Jaaskelainen, *Polym. Eng. Sci.*, 42, 1600 (2002).
- J. Pirskanen, J. Immonen, V. Kalima, J. Pietarinen, S. Siitonen, M. Kuittinen, K. Monkkonen, T. Pakkanen, M. Suvanto, and E.J. Paakonen, *Plast. Rubber Compos.*, 34, 222 (2005).

- M. Yoshii, H. Kuramoto, and Y. Ochiai, *Polym. Eng. Sci.*, 38, 1587 (1998).
- 21. M. Yoshii, H. Kuramoto, T. Kawana, and K. Kato, *Polym. Eng. Sci.*, **36**, 819 (1996).
- 22. S. Kim, C.-S. Shiau, B.H. Kim, and D. Yao, *Polym. Plast. Technol. Eng.*, 46, 1031 (2007).
- 23. D. Yao, T.E. Kimerling, and B. Kim, *Polym. Eng. Sci.*, **46**, 938 (2006).
- 24. C.-H. Wu and W.-S. Chen, Sens. Actuators A, 125, 367 (2006).
- 25. M. Blochowiak, T. Pakula, H.-J. Butt, M. Bruch, and G. Floudas, *J. Chem. Phys.*, **124**, art no. 134903 (2006).
- D. Delaunay, P. Le Bot, R. Fulchiron, J.F. Luye, and G. Regnier, *Polym. Eng. Sci.*, 40, 1682 (2000).
- 27. Moldflow Plastics Insight (MPI) 6.1, *Moldflow Corporation*, Framingham, MA, USA (2007).
- 28. H.J. Gramberg, J.C.W. van Vroonhoven, and A.A.F. van de Ven, *Eur. J. Mech. B Fluid.*, **23**, 571 (2004).