

Characterization of Micro Injection Molding Process for the Replication of Micro/Nano Features Using Bulk Metallic Glass Insert

Nan Zhang, David J. Browne, and Michael D. Gilchrist

Abstract—Microsystems are motivating the development of complex, net-shape products weighing a few milligrams or having micro/nano features. Such small components or micro/nano features are subject to extreme shear rates and thermal gradients in the micro injection molding process due to their large surface to volume ratio. Detailed process monitoring and characterization are desirable to create a viable manufacturing process with acceptable part quality for MEMS and Microsystems. This work covers the replication of micro/nano scale features using Bulk Metallic Glass (BMG), implementation of a suite of PT (pressure and temperature) sensors on a commercial reciprocating micro injection molding machine, and detailed analysis of the relationship between process-rheology-replication. The results indicate that injection velocity dominates the average viscosity of polymer melts; holding pressure can adjust the input pressure history for micro/nano features and mold temperature can enhance feature filling by elevating the polymer-mold interface temperature. Tailored strategies to set machine parameters for different molds and plastics can be developed to meet the quality requirement for both small components and micro/nano features.

Index Terms—Micro injection molding, process-rheology characterization, micro/nano feature replication

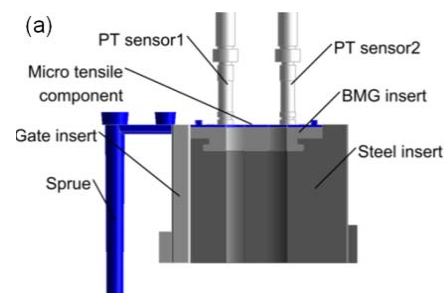
I. INTRODUCTION

MEMS and Microsystems (MST) technologies are creating a huge market for micro components and parts with micro/nano scale features[1]-[3], such as micro gears and microfluidic devices. Micro injection molding is a key enabling fabrication technology for mass production of polymer micro components. However, due to their high surface to volume ratio, micro/nano features are subject to high thermal gradients and are quick to solidify. Any resulting inaccuracy of the features can affect part functionality. Detailed process monitoring and quality control are required in order to make micro injection molding a visible manufacturing process with acceptable quality products. However, different machine configuration, dynamic response and metering capability can all impact metering accuracy, process repeatability, material thermo-dynamic behavior and finally affect the filling of micro/nano cavity, micro part quality and its internal microstructures. In conventional process characterization, researchers are more concerned with the effect of selected

machine parameter settings on final part quality[4], [5]. Some attempts have been made to understand the thermo-mechanical behavior of polymer melts in micro injection molding by means of in-line process monitoring[6]-[9]. In our previous work[10], based on a reciprocating micro injection molding machine, we found that the machine transition from velocity to pressure control (V-P transition) during micro injection molding will last 10ms. This time scale is comparable to the cavity filling time 16~24ms. In the present work, we used a screw velocity to optimize the shot size in order to eliminate effect of the V-P transition on micro cavity filling. Using this optimization, we measured the thermo-rheological behavior of polymer melt with two combined PT sensors. By using a Bulk Metallic Glass (BMG) mold insert, we successfully replicated a series of micron and submicron scale features[2], [3]. Based on process and rheological characterization, we can now propose process based quality control strategies for replicating micro/nano features.

II. EXPERIMENTS

All the experiments were implemented using a Fanuc Roboshot S-2000i 15B reciprocating micro injection molding machine. The mold cavity was formed by a steel mold insert with an embedded BMG insert on the top, as displayed in Fig. 1 (a). The cavity pressure was monitored by two combined PT sensors. A FEI Quanta 3D FEG Dual Beam FIB was used to machine the sub-micron and nano scale features on the surface of the BMG insert, as shown in Fig. 1 (b). Pebax 7233 SA01 was used as the molding material in this study. A half factorial experimental design was used to statistically study the effect of process parameters on material viscosity and micro feature replication, as shown in Table I. Three important machine parameters were selected: injection velocity (V_i), holding pressure (P_h) and mold temperature (T_m). The shot size was optimized based on injection screw velocity for each process condition and this will be discussed in a future publication.



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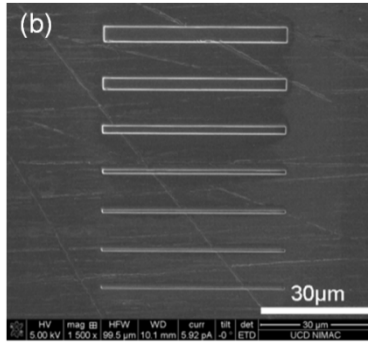


Fig. 1. Mold and features: (a) mold insert, (d) micro and submicron channels on BMG

TABLE I: EXPERIMENTAL DESIGN MATRIX

Process conditions	V_i [mm/s]	P_h [MPa]	T_m [°C]
1	250	70	100
2	250	70	100
3	250	50	60
4	100	70	60
5	250	50	60
6	100	50	100
7	100	50	100
8	100	70	60

III. RESULTS AND DISCUSSION

A. Micro/Nano Feature Replication

Each measurement sample was randomly selected from 30 parts which were molded under the same combination of machine parameters. The replicated heights of features were measured by a Veeco optical profilometer. As shown in Fig. 2 (a), the designed features were well replicated with the thinnest line being ~300nm in width. The average height of the third feature counting from right hand side in Fig. 2 (a) was used to evaluate replication quality under different process conditions. Statistical analysis shown in Fig. 2 (b) indicates that both the injection velocity and mold temperature have a significant effect on feature replication. The effect of mold temperature is more significant than injection velocity.

B. Rheological Behavior of Polymer Melts

A slit flow model was used to evaluate the rheological behavior of polymer melts during filling of a micro dog-bone cavity. With the assumptions of a fully developed steady state laminar flow with no-slip on the wall, the viscosity can be calculated by monitoring the amount of polymer exiting from the slit die per unit time (Q) for a given pressure drop (ΔP)[11]. A detail characterization of thermo-rheology behavior of polymers in micro injection molding process has been reported in our previous publication[12]. The apparent shear rate and real shear stress in the slit model are given by

$$\dot{\gamma}_{w(app)} = \frac{6Q}{wh^2} \quad (1)$$

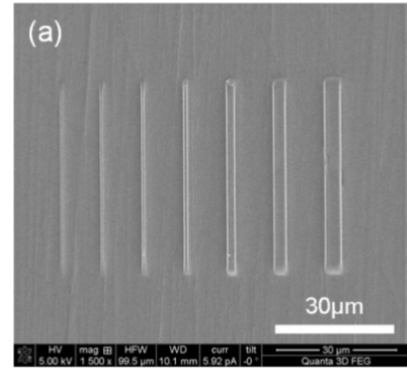
and when the ratio between width and thickness of a rectangular channel is below 10, shear stress at the wall for Newtonian fluids can be represented by

$$\tau_{w(real)} = \frac{w \cdot h}{2(w+h)} \left(\frac{-\Delta P}{L} \right) \quad (2)$$

where w is channel width, h is channel height and L is the gauge length, as shown in Fig. 3. The apparent viscosity η_a at apparent wall shear rate is given as

$$\eta_a = \frac{\tau_{w(real)}}{\dot{\gamma}_{w(app)}} \quad (3)$$

As shown in Fig. 4 (a), it is clear that the melt front travels from the inlet sensor to the outlet sensor during time Δt_1 . Pressure drop is uniform during Δt_2 when the melt front flows to the end of the part. The average pressure drop during Δt_2 was used to identify the pressure gradient in Eq. 2. The volume flow rate Q was represented by the volume of the part from the inlet sensor to the outlet sensor over the filling time Δt_1 . Based on the slit flow model, five consecutive cycles were selected to calculate the apparent viscosity. As indicated in Fig. 4 (b), the injection velocity has a dominant effect on viscosity although mold temperature and holding pressure also have an influence on viscosity.



(b) Normal Plot of the Standardized Effects

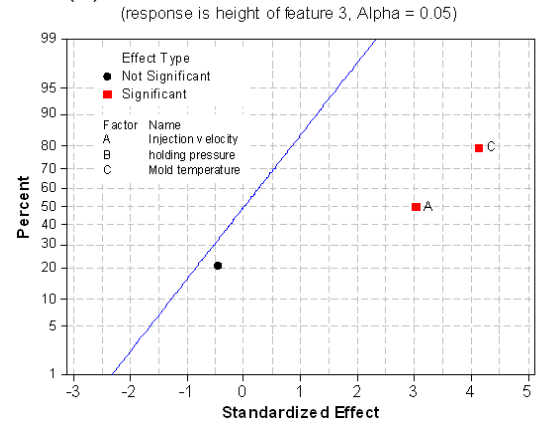


Fig. 2. (a) Replicated micro and submicron features by Pebax (rotated 90° relative to the master features on BMG); (b) Standardized effect of machine parameters on replication.

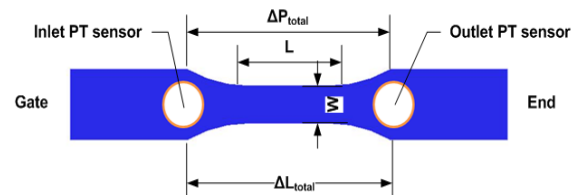


Fig. 3. Slit flow model of dog-bone cavity.

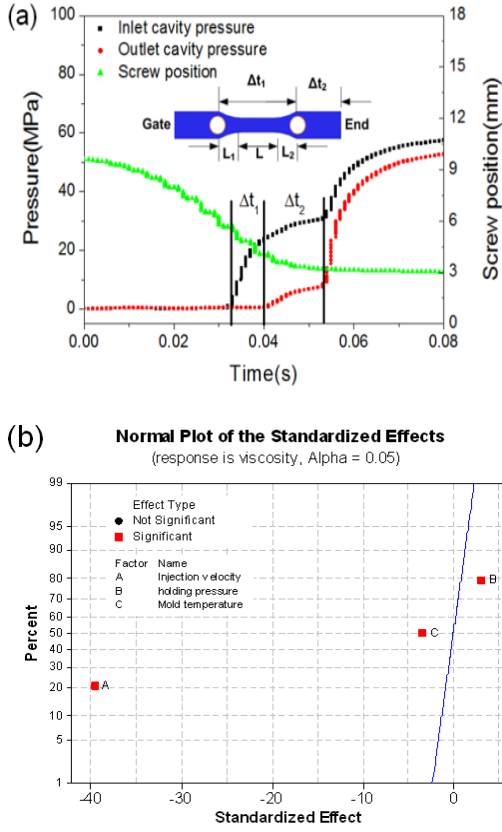


Fig. 4. (a) Typical pressure and screw position during filling of the dog-bone cavity; (b) Standardized effect of machine parameters on viscosity.

C. Process-Rheology-Replication

The filling depth of micro/nano features, as shown in Fig. 5, can be estimated by a simple pressure driven flow model, where d is filling depth, P_o is input pressure at the entrance of the micro/nano cavity, h is feature wall thickness, t_f is the filling time and η is the average viscosity.

$$d = h \left[\frac{t_f P_o}{12\eta} \right]^{1/2} \quad (4)$$

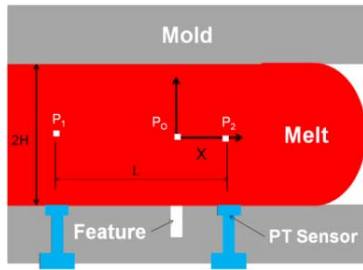


Fig. 5. A schematic of filling model for micro substrate cavity.

The filling time of a micro/nano feature can be estimated using one-dimensional heat conduction[13]

$$t_f = \frac{h^2}{\pi^2 \alpha} \ln \left[\frac{8}{\pi^2} \left(\frac{T_i - T_w}{T_s - T_w} \right) \right] \quad (5)$$

where α is the thermal diffusivity of the polymer and T_i is melt temperature, T_w is the polymer melts and mold interface temperature, T_s is solidification temperature. The melt temperature is fixed on $T_i=210^\circ\text{C}$. Therefore, the interface temperature determines the filling time of micro/nano

features. An increase of mold temperature could remarkably elevate cavity wall temperature, which would extend micro cavity filling time. A pressure driven flow model was used to estimate the input pressure for micro/nano features, as shown in Fig. 6 (a). Assuming that the flow is fully developed, the entrance effects are ignored and the flow is unidirectional, the input pressure at the micro/nano feature can be estimated[14]

$$P_o(t) = P_2 + \Delta p = P_2 + \frac{3\eta Q}{2WH^3} x \quad (6)$$

where x is the distance between sensor 2 and O and it is 1.63mm, W is gauge width, H is half thickness of dog-bone cavity, as displayed in Fig. 5. Fig. 6 (a) shows the estimated input pressure P_o for the micro features. The average pressure was used to evaluate the evolution of input pressure during the whole dog-bone part filling process. As indicated in Fig. 6 (b), only holding pressure has a significant positive effect on input pressure. It means that we can adjust cavity pressure by controlling the holding pressure.

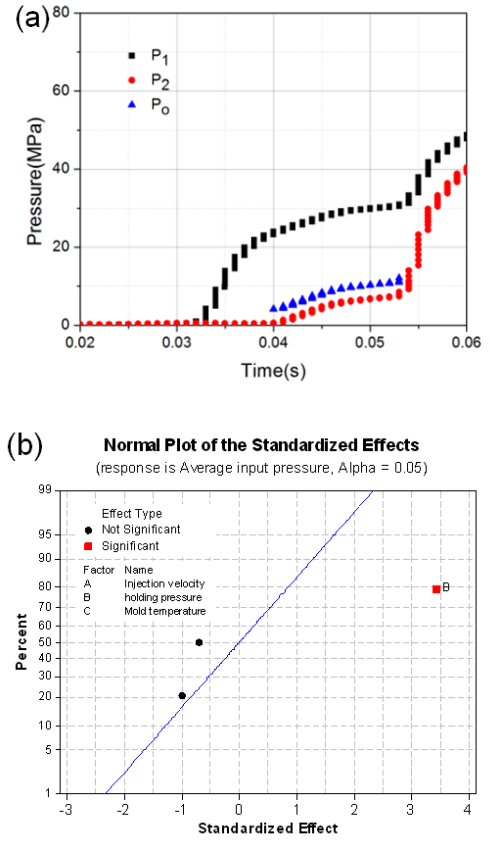


Fig. 6. (a) Estimation of input pressure of micro/nano features; (b) Statistical analysis of average input pressure

Regarding the factors (filling time, input pressure and average viscosity in Eq. (4) that directly influence replication quality of micro/nano features, we can make the following observations:

- Increase of injection velocity can significantly reduce the viscosity of polymer melt and, therefore, improve filling of micro/nano features;
- Holding pressure can change the history of input pressure during the filling process of a macro part and thus influence the filling of micro/nano features;
- Mold temperature can significantly affect the

mold-polymer interface temperature and improve the filling time of micro/nano features.

However, the statistical analysis in Fig. 2 indicates that holding pressure has no significant effect on filling of micro/nano feature. This means that feature replication is not sensitive to input pressure for our case. Decreasing melt viscosity and increasing filling time are key issues for micro/nano feature replication.

IV. CONCLUSIONS

By using PT sensors and a BMG insert, we successfully replicated some micro and submicron features and also monitored the filling process of a dog-bone cavity. Based on the slit flow model, the average viscosity was measured and characterized by statistical methods. We found that the injection velocity has a dominate effect on melt viscosity, although the mold temperature and holding pressure can also introduce some variation. The history of the input pressure was determined by holding pressure. By affecting the mold-polymer interface temperature, the filling time of micro/nano features were determined by mold temperature.

By isolating the effect of the machine parameter settings on the factors that determine feature replication, namely input pressure, interface pressure and viscosity, we found that compared to input pressure, it was the decreasing melt viscosity and increasing filling time that were more important in controlling the feature replication. Process optimization and plastic materials selection, and the use of auxiliary equipment should all aim to reduce melt viscosity and to increase micro/nano feature filling time. For a particular plastic and mold, we can also tailor machine parameters to ensure good replication of micro/nano features and, at the same time, ensure the macro part has no defects and can meet any stringent requirements for applications in Microsystems.

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