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Effect of design on the replication of micro/nano scale features by micro injection moulding

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Abstract

The replication of micro/nano scale features is of great interest for MEMS and Microsystems. However, the flow behaviour of melts into a micro/nano cavity is still not well understood. In this work, we used the micro injection moulding process to replicate micro/nano scale channels and ridges from a Bulk Metallic Glass (BMG) cavity insert. High density polyethylene (HDPE) was used as the moulding material. The influence of feature configuration, length, width, gap distance between features, location on substrate, and substrate thickness on the quality of replication was investigated. The experiments revealed that the replication of ridges, including feature edge, profile and filling distance, was sensitive to the flow direction; a critical feature length was found below which the filling of features was significantly reduced. Both the feature location and the substrate thickness had an influence on the filling of micro/nano features while the gap distance had a negligible effect on the replication of features.

Keywords: Micro injection moulding, replication quality, micro/nano features, bulk metallic glass

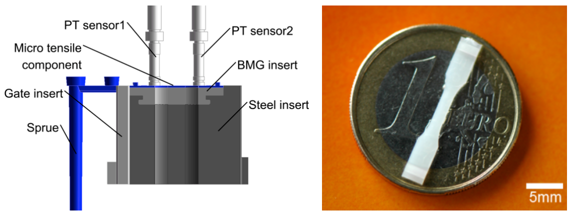
1. Introduction

The development of MEMS and Microsystems is inspiring the global trend towards miniaturization, which is creating a huge market for micro components with micro/nano scale features [1], especially microfluidic devices, which have many applications in chemical, biological and medical diagnostics [2]. Currently, the dimensions of micro channels for microfluidic devices range from 10 to 100 μm and even extend to the submicron and nanometer scale for manipulating and measuring individual molecules [3-5]. The size of nanophotonic devices, super hydrophobic surfaces and optical gratings are macroscopic in scale, but they all have surface features on the micro/nano scale [6-8]. In addition, replication accuracy is critically important for functional surfaces, such as a nanostructured matrix for DNA separation [9]. Therefore, a mass production process with high replication accuracy needs to be developed for such devices. The micro injection moulding process is a key fabrication technology to mass produce polymer micro components. However, due to high surface to volume ratios, premature solidification can occur and prevent complete filling, especially for micro/nano scale features. This work will focus on the influence that the design of features has on replication quality. The effect of feature configuration, width, length, spacing, location, and substrate thickness on the filling of micro/nano features will be studied.

2. Experimental methods

2.1. Machine and mould

All experiments were conducted using a Fanuc Roboshot S-2000i 15B reciprocating micro injection moulding machine. The mould cavity was formed by a steel mould insert with an embedded bulk metallic glass (BMG) insert on its top, as displayed in Fig. 1 (a). The dog-bone component was moulded from HDPE (HMA016) with designed thicknesses of 0.5 and 0.4mm, as shown in Fig. 1 (b).



(a) (b)

Fig. 1. Mould and moulded part: (a) bulk metallic glass insert, (b) dog-bone part.

2.2. Feature design

Focused Ion Beam (FIB) milling technology was used to machine the channels and ridges on the surface of the BMG insert. As shown in Fig. 2, four groups of features were milled near the shoulder of the dog-bone component, which was farthest away from the gate. Two groups were channels and the other two groups were ridges, which have been arranged parallel and transverse to the flow direction. The channel depths on the BMG were 2.238±0.07μm and width dimensions ranged from 4μm to 0.3μm. The heights of ridge features were 1.905±0.14μm, and widths ranged from 4μm to 0.45μm.

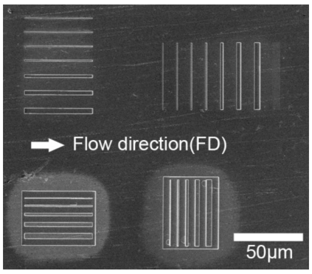
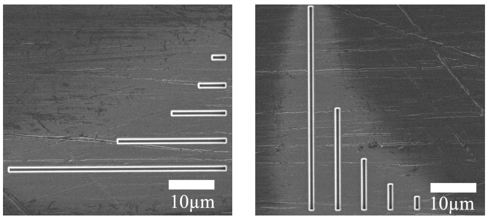


Fig. 2. Channel and ridges on BMG insert

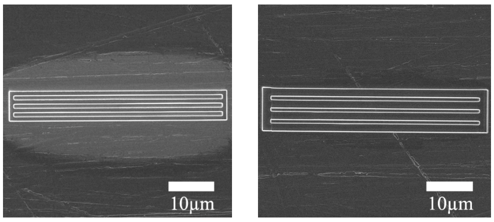
Figure 3 illustrates two groups of channels of different length, which are arranged along and against the flow direction (FD). The depth and width of these channels is 2.67±0.09μm and 1.04±0.05μm respectively with the designed length being 48, 24, 12, 6, and 3μm.



(a) (b)

Fig. 3. Channels with different length on BMG: (a) along flow direction, (b) against flow direction.

Figure 4 displays two groups of ridge features on the BMG insert with a designed gap distance of 2 and 1 μm. The ridges milled on the BMG surface are 0.98±0.044μm in width and 1.58±0.075μm in height.



(a) (b)

Fig. 4. Ridges with different gap distance on BMG: a) 1 μm, b) 2 μm.

In addition, the same designed channels as those in Fig. 2 were located at position 1 and position 2 along the flow direction in order to study the effect of feature location on cavity filling, as shown in Fig. 5.

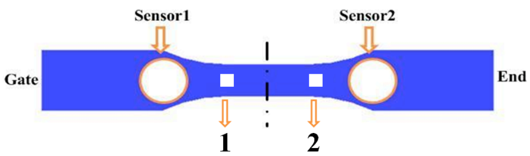
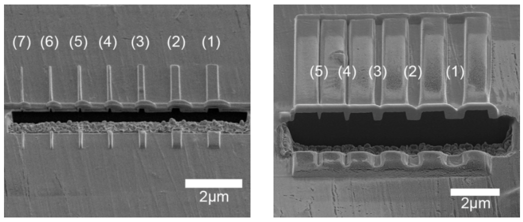


Fig. 5. Ridge locations on the BMG insert.

2.3. Measurement

Each sample that was selected for measurement was randomly selected from 30 parts which were moulded under the same combination of machine process parameters. A FIB milling technique was used to cut away a section of the features in order to observe the profile of the features. A Pt strip layer was deposited via e-beam across the ridges and channels so as to protect the feature integrity during the FIB milling process. For ridges, the profiles of features are exposed directly, as shown in Fig. 6 (a). For channels, the profiles of features can be reflected by cutting through the Pt layer, as shown in Fig. 6 (b).



(a) (b)

Fig. 6. Cross section of micro/nano features on the moulded part machined by FIB milling: (a) ridges, (b) channels.

3. Results and discussion

3.1. Effect of feature configuration and geometry

All the features are well replicated, as shown in Fig. 7. It can be seen that ridges along the flow direction have a better replication quality than those against the flow direction, especially for smaller features. On the other hand, channels along the flow direction have a similar replication quality to those against the flow direction. The relative and absolute extent of filling under the same process conditions were used to evaluate replication quality. Each ridge and channel was nominated in sequence from big to small, as indicated in Fig. 6. Figure 8 exhibits the profiles of ridges along and against the flow direction. Ridges against the flow direction present round edges and their profile has a tendency to incline with the flow direction. Ridges along the flow direction have sharp edges, especially for ridges of width greater than 1μm. Ridges smaller than 1μm width along the flow direction also exhibit greater replicated heights than those against the flow direction. This indicates that smaller features, especially nano scale features are more sensitive to the flow direction. On the other hand, channels that are aligned along the flow direction have a similar replication quality to those against the flow direction, as can be observed from Fig. 9 (a) and (b).

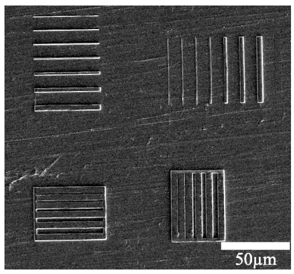


Fig. 7. Channel and ridges on HDPE component.

The relative and absolute heights of ridge filling are compared in Fig. 10. This also suggests that ridges that are aligned along the flow direction have better filling than those against the flow direction. The maximum percentage of filling is around 60% with a maximum height of 1.7 μm.

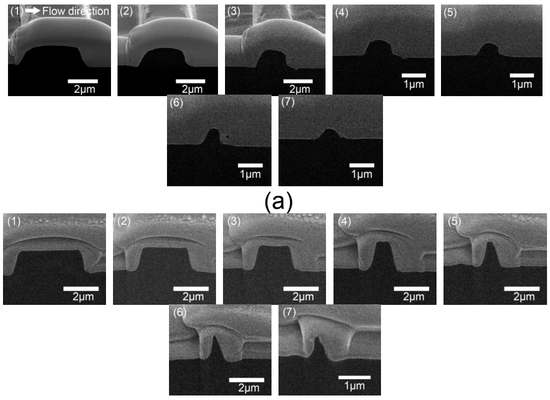


Fig. 8. Profiles of ridge features: (a*)* against flow direction, (b) along flow direction.

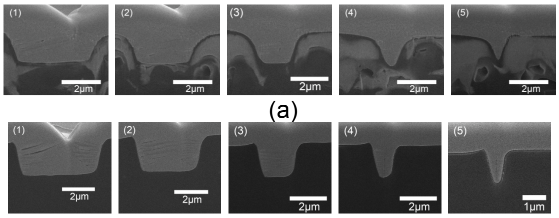


Fig. 9. Profiles of channel features: (a) against flow direction, (b) along flow direction.

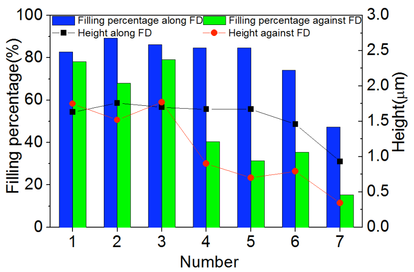


Fig. 10. Filling percentage and height for ridges. Blue (black square) and green (red circle) correspond to percentage filling (absolute height) along and against the flow direction, respectively.

The sensitivity of micro/nano features to the flow direction of polymer melt can be explained by the phenomenon of air entrapment during filling of micro/nano features. The relative position of a fountain flow front and micro/nano cavity is illustrated in Fig. 11, where *d* and *h* are the depth and thickness of the micro cavity. Assuming that laminar flow is fully developed in the macro dog-bone cavity and the melt front is a semicircle with radius *R*, the gap δ between the fountain flow front and the edge of the micro cavity can be estimated, as shown in Fig. 11 (b). Consider ridge 1 as an example: the corresponding length of cavity on the BMG insert along and against the flow direction is 50 μm and 4μm, respectively; the corresponding gaps δ are around 5μm and 0.05 μm. Clearly most of the air in the micro cavity that is aligned parallel to the flow direction can escape from the cavity during filling. On the other hand, a larger volume of air will be entrapped in the cavity that is aligned against the flow direction: this may prevent further filling of the micro cavity and also affect the profile of micro/nano ridges. This physical explanation is consistent with simulations that have been made of micro scale features [10].

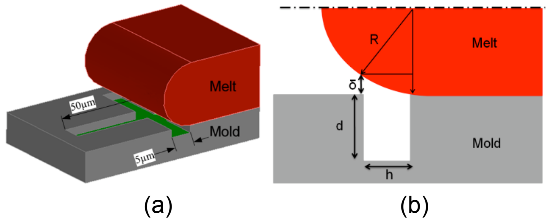


Fig. 11. Schematic representation of advancing front and micro/nano cavity: (a) 3D view, (b) 2D view.

In order to provide further insight into the influence of entrapped air on the filling of features, ridges with different lengths along and against the flow direction were replicated. As illustrated in Fig. 12, features against the flow direction have similar percentages of filling; this is smaller than those along the flow direction when feature length decreases from 48 to 6 μm. It is important to note that the percentage of filling decreases significantly to a minimum of 24% when the feature length decreases to 3 μm. The corresponding gap δ is 0.03 μm, as shown in Fig. 12(b). This suggests that there is a critical δ below which the filling of features will decrease significantly.

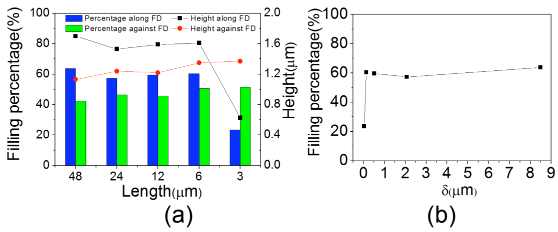


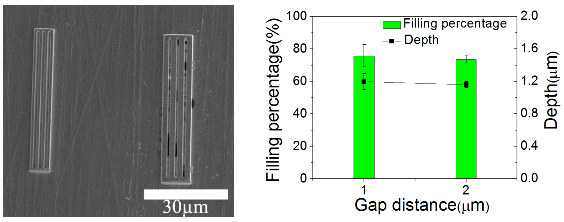
Fig. 12. (a) Filling percentage and height for features with different length, (b) filling percentage Vs. gap, δ.

3.2. Effect of channel gap distance

Figure 13 displays the replicated channel with different gap distances. They are both oriented along the flow direction with the channel width and length being around 50 μm and 1 μm, respectively. It can be seen that the gap distance does not have any significant influence on the replication of channels.

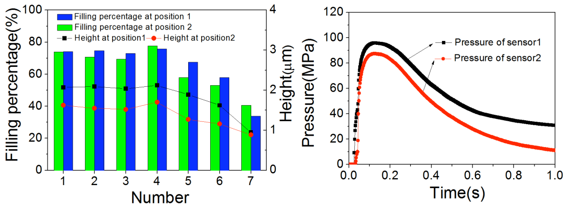
3.3. Effect of feature location

Channels were arranged at two different positions along the flow direction, as shown in Fig. 5. The filling percentage of features near the gate (position 1) and remote from the gate (position 2) displays a similar pattern, as indicated in Fig. 14. The features near the gate are slightly higher than those further from the gate. This could be explained by the entrance pressure. As shown in Fig. 14(b), the pressure at sensor1, which is nearer the gate, is greater than that further from the gate. This greater pressure might allow for further filling for micro/nano features, according to Young's analytical model [11] and Cao's numerical model [12]. Both models used cavity pressure as an input to describe the filling of polymer into micro features.



(a) (b)

Fig. 13. (a) Channels on HDPE, (b) filling percentage and depth.

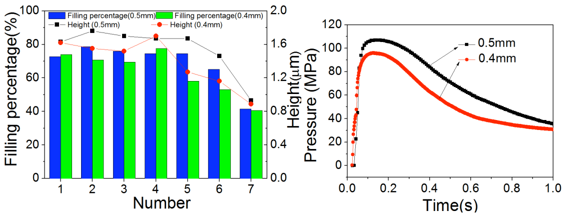


(a) (b)

Fig. 14. (a) Filling percentage and height for features along and against flow direction, (b) cavity pressure for sensor1 and sensor2.

3.4. Effect of substrate thickness

The same channels that were aligned along the flow direction as shown in Fig. 2 were milled on dog-bone inserts with cavity thicknesses of 0.5mm and 0.4mm. Both sets of channels were moulded under the same process conditions. The filling percentage of features has the similar pattern, i.e., gradually decreasing with feature width, as shown in Fig. 15. Features replicated on the 0.5mm dog-bone have greater filling than those on the 0.4mm part. This could be because the cavity pressure of the 0.5mm part is higher than that of the 0.4mm part, as indicated in Fig 15 (b).



(a) (b)

Fig. 15. (a) Filling percentage and height for features along and against flow direction, (b) cavity pressure of sensor1 for 0.5mm and 0.4mm dog-bone components.

4. Conclusions

In this study, the micro/nano scale ridges and channels were well replicated with the micro injection moulding process by using a BMG insert. The experiments indicate that the quality of micro/nano features is very sensitive to the flow direction. The ridges that are oriented against the flow direction have round edges and their profiles are inclined with the flow direction. On the other hand, ridges that are parallel to the flow direction have the sharp edges and better replicated heights. Channels exhibit fewer significant differences than ridges. The sensitivity of feature replication to the flow direction can be explained by entrapped air in a micro cavity. In addition, the filling of features decreases with their width, especially for sub-micron features. It is found that a critical feature length exists, below which the filling of the feature will decrease significantly. Gap distance between channels has no significant effect on feature filling. Instead, filling was slightly influenced by feature location and substrate thickness, both of which are related to cavity pressure. Consequently, it is important that features and their configuration are designed carefully in order to properly replicate micro/nano scale features.

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