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Injection Mold Process Optimization for Surface Microfeature Control

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INJECTION MOLD PROCESS OPTIMIZATION FOR SURFACE MICROFEATURE CONTROL

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INTRODUCTION

A method for creating regular arrays of surface features in the 10µm to 200µm range over large areas in metallic materials enables the use of treated surfaces on injection molds. This surface control is used for manufacturing products with controllable optical, tribological, heat transfer, and surface tension properties. However, the flow, filling, and solidification behavior of molten polymer at the micro scale is not well understood.

Therefore, the purpose of this study is to derive a range of robust solutions for injection molding of these micro-featured surfaces. The approach includes numerical simulation of flow under different molding conditions, which drives input variable and range selection of a large design of experiments study. This study uses critical inputs of the molding process, mold geometry, and working materials, and determines a range of feasible solutions to recreate these micro structures without filling or demolding defects. Five different molding parameters hypothesized as most influential in molding microstructures were varied and the resultant micro-features characterized using 3D surface profiling white light interferometry and scanning electron microscopy. Regression responses were determined and optimal value ranges for the key input parameters were identified and independent tests run to verify the results. The five parameters tested are: injection pressure, injection velocity, mold temperature, melt temperature and shape of micro structures. These tests were carried out in both HDPE and EPDM/PP alloy [1] materials using different mold insert materials and coatings.

The results obtained from these tests gave us a clear indication of how each of the above parameters controls the formation of molded microfeatures, and how parameters interact. In this case mold temperature was found to be the most critical factor, with a sensitivity of only a few degrees greatly improving the micro feature formation. The biggest concern was uniformity of micro features across the molded surface. Based on this understanding we were also able to simulate macroscopic mold filling conditions and verify homogeneous filling across the molded surface. These experimental results are used to drive a predictive tool for process planning of complete undamaged feature formation at the micro scale and uniformity at the macro scale.

MICROFEATURE MOLD DEVELOPMENT

The injection mold inserts were fabricated by Hoowaki LLC using a process with certain proprietary segments. The process begins with silicon micro-fabrication to create an original silicon mold. Because the silicon is brittle, a series of intermediate materials are cast, molded, and formed to create the durable nickel and steel molds used in the present study [2]-[4].

REVIEW OF MICROFEATURE MOLDING

Embossing Pillars

In the past the impact of polymer film thickness and cavity size on polymer flow during embossing of similar micro features has been studied for the nanoimprint lithography process [5]. It was found that polymer deformation and fill time is governed by location and rate of polymer shear during imprinting, exhibiting deformation predominantly close to the vertical side wall that can result in either single peak or dual peak deformation modes. There is no reference to observation of such modes in micro-injection molding.

Microinjection Molding

Chu et al. [6] investigated the effects of various injection molding process parameters on the micromolding process and part quality. They

estimated the processing conditions during the cavity filing stage in a plunger micro injection molding system by using short-shot trials and by analyzing the data obtained from tracing the evolution of injection pressure, runner pressure, and plunger position, at the millisecond time scale. They did this study for three different polymers: POM, HDPE, and PC and through statistical analysis found injection speed to be most significant factor while the effects of mold and melt temperature varied from material to material.
In our study although Injection velocity appeared to be a significant factor, mold temperature was found to be most significant factor for injection molding micro-features.

DESIGN OF EXPERIMENTS APPROACH

Step 1: A two cavity injection mold was designed to produce flat rectangular test pieces (44mm x 24mm). Micro features were produced by placing patterns with 20 to 100 micron holes inside the cavities.

Step 2: Mold material and coating were screened for measures of goodness related to uniformity of micro features on the pattern, transferability and demolding. Several different materials were tested and summary results shown in Table 1.

Table 1. Pattern material characteristics

Material	Uniformity of micro-features on patterns	Transferability of micro-features to injection molded surface	Remarks
Silicon rubber	Good	Average	De-molding issues
Epoxy	Average	Bad	High de-molding issues
Stainless steel	Good	Good	No de-molding issues
Teflon coated stainless steel	Good	Very good	No de-molding issues
Ni coated copper	Very good	Very good	Excellent de- molding

Based on these results, stainless steel and Ni coated copper were selected as pattern material for the extended study.

Step 3: A fractional design of experiments (DOE) study was carried out to quantify the effect of the following injection molding parameters on microfeature formation: injection pressure, melt temperature, mold temperature, injection velocity, and cavity thickness. In addition to these, the effect of shape and size of micro-features was also tested.

The quality of micro-feature formation / transferability was determined by analyzing the injection molded surface under Zygo White-Light 3D Surface Profiler. This was done by measuring the height of micro-features at 3 different locations over the molded surface to test uniformity and to see whether or not the target height has been achieved.

In order to understand the effect of macro flow characteristics on the formation of microfeatures, the same test was carried out with component thickness of both 1.5mm and 3.5mm.

Two different polymers, HDPE and EPDM/PP alloy were used for the tests. The feature height H was recorded in area 1, 2, and 3 and denoted in Figure 1.

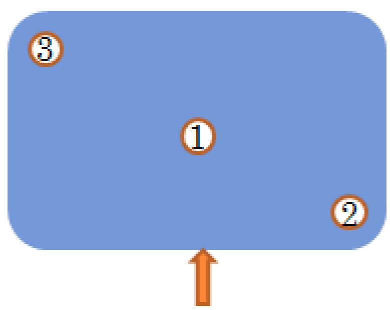

Figure 1. H_1, H_2, and H_3 represent the sample feature height in area 1, 2 and 3 respectively; the arrow denotes the gate position.

The sensitivity plot shown in Figure 2 represents the response height variation with injection pressure for HDPE material. In this plot, the dashed line represents the mold depth compensated for expected material shrinkage. The effects of the other molding parameters on micro-feature formation have been represented similarly.

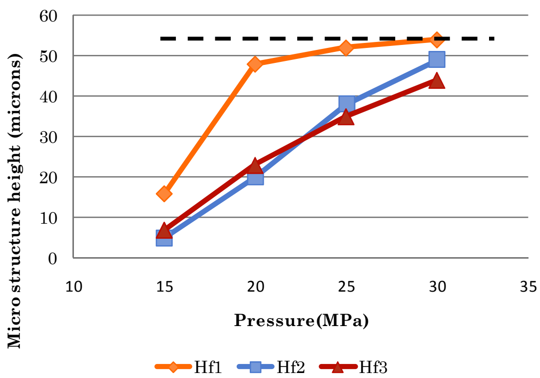

Figure 2. Effect of injection pressure variation on micro-feature height formed with HDPE

The same single-variable response in EPDM/PP alloy material is shown in Figure 3.

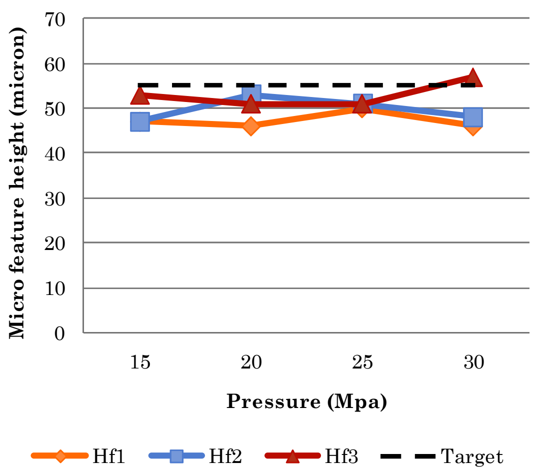

Figure 3. Effect of injection pressure variation on micro-feature height formed with EPDM/PP alloy.

It is apparent that material properties will have a significant interaction effect. Therefore, material-specific regression models are created for the materials tested.

Results

Multi-variable regression is performed for both HDPE and EPDM/PP alloy materials by ANOVA identification of significant factors and model reduction to include only significant variables and interactions. The resultant model for prediction of feature height in the center of a test sample in HDPE with circular micro features is

$$H_1 = -1031.7 + 18.7P + 2.49T_0 + 2.24V - 0.37P^2 \quad (1)$$

In this model, injection pressure (P, MPa), injection velocity (V, mm/s), and mold temperature (T_0, K) are significant. The model accounts for 83% of the variation observed in microfeature height. The most significant parameters are injection pressure and mold temperature. The model predictions vs. experimental runs are shown in Figure 4.

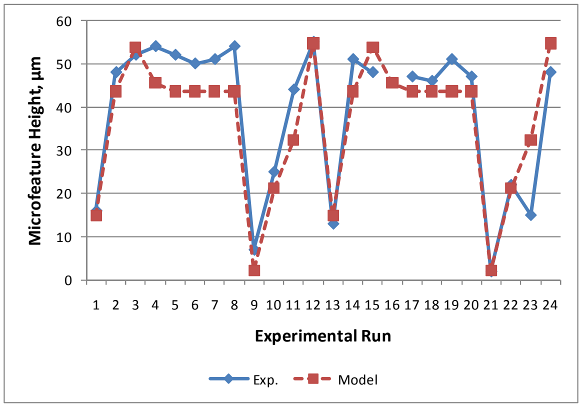

Figure 4. Regression model prediction of microfeature height in plate center (Mold 002A, circular features, HDPE material).

Optimization

For macro molding the range for the tested parameters seems high when compared with traditional injection molding practice. For example the component looks same at both 15 MPa injection pressure and 30 MPa injection pressure without micro-features; however in the case of micro molding we screened experiments for a wider range of values than traditionally used. The developed regression model was used to plan a feasible process setting for maximum feature height. As discussed in the measurement section, we also observed anomalous "spike" features at the microfeature edges; the optimal process was also designed to minimize this spike height. The resultant optimized value for micro-feature formation with HDPE was: Injection pressure 25 MPa, Injection velocity 20 mm/sec, Melt temperature 280℃ and Mold temperature 140℃.

This parameter setting was tested across a range of mold materials and coatings. Component thickness, shape and size of micro-features did not affect the process much at the optimized value; well-formed micro-features were obtained irrespective of changes in component thickness, shape and size of pores in patterns.

MEASUREMENT VALIDATION

Surface Height Geometry

When the micro-features formed by injection molding were analyzed under Zygo White-Light 3D Surface Profiler some spike like features were observed, mostly at the edges. The amount of these spike like features decreased when Ni-Cu patterns were used for molding. However when the same samples were observed under SEM no evidence of spikes was found. A SWLI image of a part with numerous spike anomalies is shown in Figure 5, and a part with few spikes is given in Figure 6.

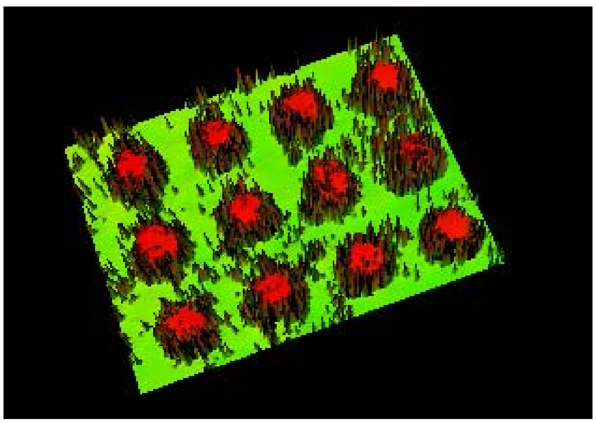

Figure 5. 3D surface profile of micro-features formed with stainless steel template showing spike like structure at the edges.

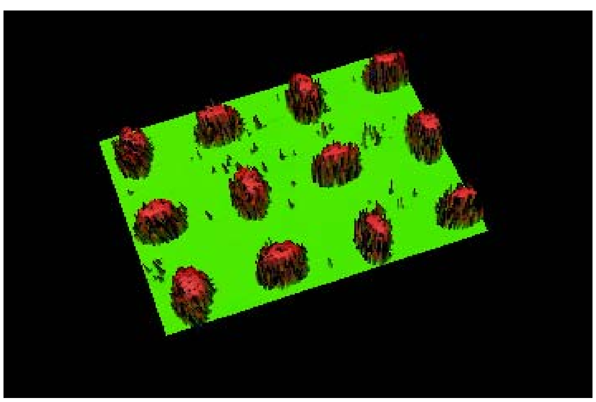

Figure 6. 3D surface profile of micro-features formed with Nickel coated Copper template showing reduced spike like structure at the edges.

Initially it was hypothesized that the spike features were demolding defects due to adhesion at the feature wall, as some observation of tearaway microfeatures that remained in the mold had been observed in extreme cases. Investigation of these anomolies was carried out using scanning electron microscopy but no evidence of such spike like structures was found under SEM giving rise to a possibility that these structures might just be measurement artifact resulting from software issue where the sharp high aspect features were out of bounds for some light reflection data smoothing algorithm used by the SWLI. An SEM image of a “spiky” part is given in Figure 7.

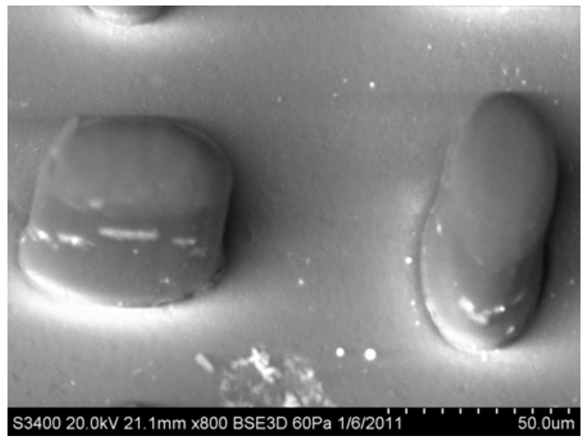

Figure 7. SEM Image of Formed Structures. The structures filled completely, some geometric inconsistencies were noted at the outer edges but there was no evidence of spike-like structures.

Microscopic Observations

SEM images validated our findings about the effect of various injection molding parameters such as injection pressure, melt temperature, mold temperature, and injection velocity on formation/transferability of micro-features. Figure 8 shows a representative comparison of HDPE samples for high and low values of the levels tested.

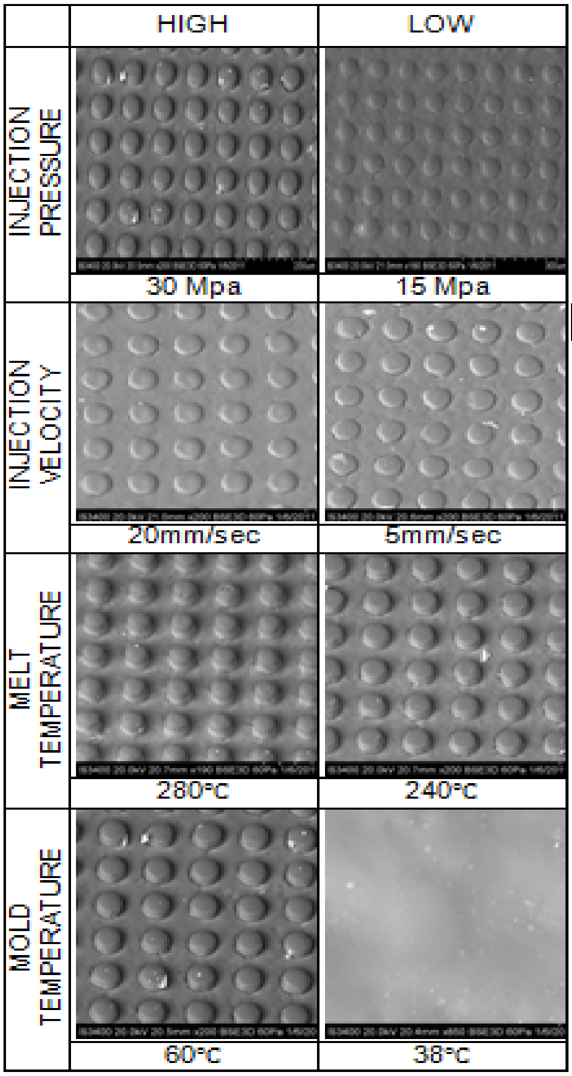

Figure 8. SEM Images of injection molded micro-features at various test conditions.

Injection pressure shows fully-formed structures at the higher level; melt temperature variation had little effect, and mold temperature variation was significant. This is consistent with the regression model results.

The feasible process input values determined from the regression model were run, with geometric results shown in Figure 9. Structures are fully formed and geometrically consistent. Some surface inconsistencies in the formed micro-features can be attributed to the features present in the molding template itself as shown in Figure 10.

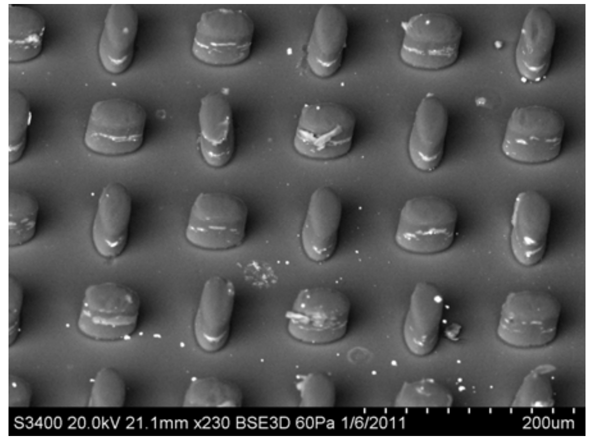

Figure 9. Microscopic Image of Formed Structures at optimal condition. The structures filled completely, but some geometric inconsistencies were noted at the outer edges.

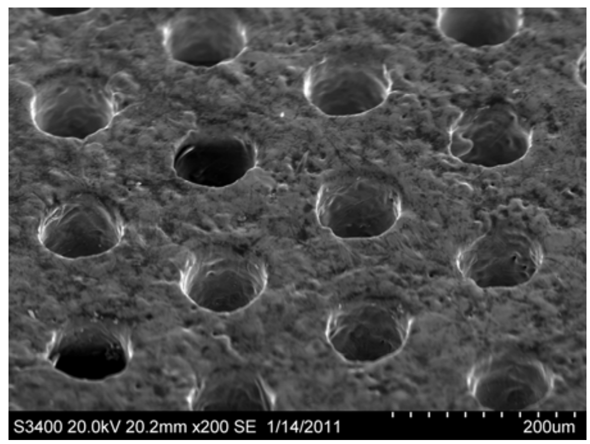

Figure 10. Microscopic Image of holes in molding templates showing inconsistencies which resulted in inconsistencies in formed micro-features. Similar templates were used for experiments.

MACROSCOPIC FLOW SIMULATION

We tried to simulate the filling process for micro-features using Autodesk Moldflow and compare results with experimental data obtained, but were unable to simulate the process at such micro level mainly due to meshing limitations. However, we were able to simulate macroscopic filling of the mold cavity and predict packing pressures, temperature and viscosity at filling for different mold conditions. An example macroscopic simulation is shown in Figure 11.

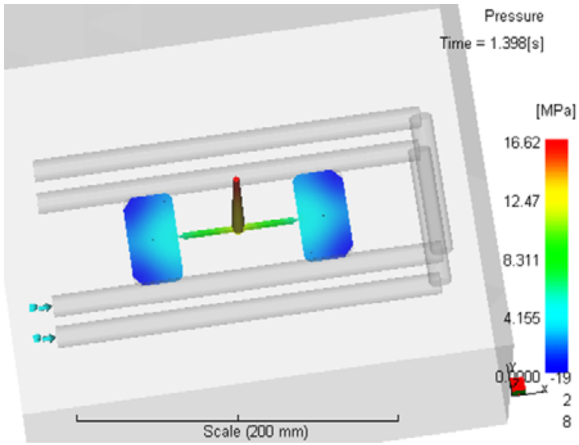

Figure 11. Simulation of pressure distribution at filling, HPDE material.

The predicted pressure profile variation used in the regression predictive model corresponds with variation in height observed at different points across the specimen (see Figure 1).

CONCLUSIONS

This study was used to derive a range of robust solutions for injection molding of micro-featured surfaces with different polymers. Feasible conditions to form these micro-features were obtained for two different polymers, HDPE and EPDM/PP alloy.

Using Design of Experiments technique, a regression model was derived for predicting the height of surface microfeatures in an HDPE injection molding operation. Similar models are also derived for height prediction in different areas of the mold and in a second material. Future work will continue this effort in a wider range of polymer and mold materials.

Future work in flow simulation for microfeatures will be to isolate and scale the microfeatures for accurate meshing, while maintaining constant nondimensional flow properties (*e.g.*, Reynolds number) for accuracy. Also, the numerical simulation results will be combined with the different regression analyses to improve the distribution of height predictions and make a better feasible process plan.

Reasons for the surface residue or delamination appearance are being investigated.

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