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Publisher's version / Version de l'éditeur:

<https://doi.org/10.3139/217.2264>

International Polymer Processing, 2009, 3, pp. 288-297, 2009-03-01

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MICRO REPLICATION BY COMPRESSION INJECTION MOLDING

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Abstract - The replication of polymeric microstructures on a flat surface is not easily achieved by conventional injection molding, because of the required micro-dimensional control and the stringent tolerances of most applications. Moreover, the flow behaviour of melts in micro cavities remains not well understood and challenging. On the other hand, injection compression molding is an established process for the manufacturing of optical storage media, like compact discs (CD) or digital versatile discs (DVD), with grooves and pits at the micro-scale. The difficulties arise mainly from two sources: lack of adequate filling because of premature freezing of features with very small thicknesses and excessive deformation during ejection due to high friction at the polymer-metal interface. In this work, a study is carried out to investigate the effect of process parameters on the replication of various microstructures on a flat disk using compression microinjection molding. A commercial micro-injection molding machine has been used in the study. Two optical grade

polymers poly(methyl methacrylate) (PMMA) and cyclic olefin polymer (COP) were used in conjunction with various mold inserts to reproduce the embedded microstructures. The dimensions of the microstructures on the inserts and molded parts were measured with a confocal profiler. A transcription ratio was defined to assess the quality of the replication. The design of experiment (DOE) method was used to obtain correlations between the process parameters and the development of the microstructure during injection compression molding.

Introduction

The trend towards miniaturization of plastic devices in various fields of application has been accompanied with the growth of micro-fabrication processes such as micro injection molding (μ -IM) and hot embossing (Chien, 2006, Hecke and Schomburg, 2004,). The latter process is a technique of imprinting microstructures by pressing a heated mold insert onto a polymer substrate held above its transition temperature. It provides an excellent transcription of micro patterns, but cycle times can be as long as 30 minutes (Hecke and Schomburg, 2004,), which is too long for a mass production process. Micro injection molding is basically similar to conventional injection molding (CIM). It is used to make parts of either very small size (few mm) and weight (few grams down to milligrams) or macro parts (few cm) with embedded patterned microstructures (microns). Micro gears, micro needle arrays, medical implants such as plates and screws for bone fracture, micro-switches and sensors, and accelerators are but a few of the products that belong to the first group, while micro lens arrays and micro-fluidic plates are part of the second category. The effect of micro injection molding parameters was studied experimentally by Zhao et al. (2003) using a mold for spur gears with diameters down to 1 mm. Micro-injection molding has a very short cycle time, which can be measured in seconds. Therefore, it is ideally suited for fabrication in large quantities. However, replication of patterned microstructures by injection molding is often difficult to carry out (Guo et al. 2007, Su et al., 2004). Although μ -IM is basically similar to conventional injection molding, the very small microstructure dimensions present some serious obstacles. These include early freezing-off, difficult filling and demolding of parts with high aspect ratio features, high injection velocities and pressures leading to high molecular orientation and residual stresses level. An example taken from (Hétu et al., 2005) illustrating such difficulties is shown in Fig. 1. The circular mold insert consisted of trenches of various shapes, 200 μ m wide and 1mm deep, giving an aspect ratio of 5. The micro features were not completely achieved at the end of molding, contrary to the predictions by the 3D numerical simulation. During filling of the cavity, the melt initially fills

easily the circular thick space above the trenches (micro-cavities). Flow into the thin channels of the trenches is minimal during this period, then proceeds with a much lower velocity profile depending on the local pressure. On the contrary, the heat transfer from the melt to the surrounding walls is much faster which makes it even more difficult to completely fill the trenches before freezing off takes place. It was found, both experimentally and numerically, that the square shaped structures filled better than the cylindrical pins. This was most probably due to the fact that cooling was less intense at the corners, allowing for more filling. It was also noted that the trenches farthest from the gate were filled much better than those closer to it. This result can be explained by the fact that the polymer around the entrance of the trenches closest to the gate had a longer cooling time before pressure build-up, resulting in lower temperature and higher viscosity and consequently, lack of complete filling during the packing-holding phase. This observation is related to the so-called "time-to-pressure", i.e., faster pressure buildup at the entrance of the micro-cavities yields better microstructures replication (Wimberger-Friedl et al., 2003). The heat transfer coefficient as well as slip at the wall were shown to play a critical role during flow over small channels (Yu et al., 2003).

An interesting alternative to hot embossing and micro-injection molding is the micro-injection compression molding (μ -ICM) process. Injection compression molding (ICM) is the process of choice to produce CDs and DVDs. The process consists of injecting the melt into the cavity, while the mold is not totally closed. This leads to an initial cavity filling under lower pressure than if the mold is closed, as in conventional injection molding. After the injection stage, the mold closes to compress the melt and to completely fill the cavity. Figure 2 shows schematically the two stages just described. Replication of pits on a CD by compression injection molding is somehow made easy by the low aspect ratio of the pits (< 1), which makes demolding less of a problem. Overall, the compression injection molding process results in less molecular orientation, molded-in stresses, shrinkage and warpage, compared to conventional injection molding (Turng, 2001). Some researchers also used μ -ICM as a prototyping process to fabricate light-guiding plates for digital

cameras and diffractive optical elements from amorphous polymers (Chen and Kao, 2008, Shen et al., 2006, Shen, 2007, Tseng and Liao, 2003). Results indicate that μ -ICM was more effective than ICM and conventional injection molding in obtaining the highest transfer ratio of grooves for diffractive optical elements (Chen and Kao, 2008). Similar results were found in the comparative study by Shen et al. (2006, 2007) on height replication of a light-guiding plate with embedded microstructures by μ -IM and μ -ICM. They show that mold temperature is clearly the most important factor for both processes. Packing pressure and melt temperature were the next most important processing parameters for μ -IM, while mold displacement distance during compression and melt temperature were next most significant for μ -ICM. A similar study was done by Wu and Chen (2006) on molding optical gratings having a depth of 1.5 μm , but they used a 50 ton injection molding machine. While their results agreed with those obtained by Shen et al., as far as injection molding is concerned, they found that the diffraction patterns were best replicated by ICM and that the most important parameter was compression speed followed by compression time, injection speed and mold temperature. Using an experimental design (Tagushi) approach, Tseng and Liao (2003) employed both μ -IM and μ -ICM to mold diffractive optical elements and analyzed the quality of their replication, as well as their efficiency in transmitting light. They obtained better results with μ -ICM, and they listed the most important processing parameters as injection compression speed, injection pressure and compression gap. The results of Tseng and Liao (2003) partly contradict those of Shen et al. (2006, 2007), as the former did not find mold temperature to have the most positive effect on the quality of microstructure replication. Most of the previous work focused on the practical aspect of developing a specific application. Given the insufficient experimental work on μ -ICM that is available in the literature and the contradictory results obtained so far, the objective of this study is to investigate the effect of processing conditions on the replication of microstructures using μ -ICM in conjunction with two different amorphous polymers: PMMA and a cyclic olefin polymer, COP. We attempt to establish qualitative correlations between

the processing conditions and the degree of replication of particular micro patterns from a circular mold insert. The molding tests were conducted according to a full-factorial experimental plan with full resolution, so that each parameter can be unambiguously evaluated.

Experimental

Injection molding machine

The molding tests were carried out using a Battenfeld Microsystem 50 injection molding machine. The basic injection unit of the machine consists of three components, as shown in Fig. 3. After melting in the 45° inclined plastication unit, the polymer is delivered through a shut-off valve to the vertical dosing unit, where the required volume is calibrated using a pressure-controlled sensing device. The molten polymer is then transferred by the metering piston to the injection unit, where an injection piston moves forward and pushes the melt through the front nozzle to fill the mold. The mold fixed plate is centrally gated through a 5 mm port (nozzle), while the mobile plate holds an insert with a series of variously shaped microstructures.

Mold insert and microstructures

A 100 mm etched silicon wafer master, containing seven zones with various microstructures, was used to make the circular mold insert used in this study, as shown in Fig. 4. The silicon master was electroplated using a Ni-Co bath. The seven inserts were then cut from the metallic disk, and their back faces were polished to a smooth surface. Only insert 2 was used in this study. A schematic representation of the corresponding microstructures is shown in Fig. 5. Locations 1, 2 and 4 of insert 2 are the focus of this study. The microstructures consist of channels or walls having a depth of 20 μm and a width of 20 or 40 μm , with the exception of location 4 which contains two rhombi filled with round and square 20 μm height pillars, as shown in Fig. 6. All molded parts have a diameter and thickness of 17 mm and 1 mm, respectively.

Materials

A cyclo olefin polymer (COP), Zeonor 1060R from Zeon Chemicals, and a poly(methyl methacrylate), PMMA M30 from Cyro Industries were used for the tests. Both are optical grade amorphous polymers, with melt indices of 14 g/10 min (230 °C; 21.2 N) and 24 g/10 min (230 °C; 37.3 N), respectively. The relative ease of flow of each polymer is better represented by the full viscosity versus shear rate curves, shown in Fig. 7. The viscosity was measured at three different temperatures, taken within the corresponding processing window for injection moulding, using the RH-7 Rosand capillary rheometer (Malvern Instruments Ltd., UK). During the filling-compression stages, the shear rate range can be anywhere between 1 to 10^5 s^{-1} with the maximum possibly at the gate. Within this range, shear thinning (i.e. rate of decrease of viscosity with shear rate) is more pronounced with PMMA, although its viscosity is higher, particularly in the low shear rate range, where compression takes place. Therefore, it would seem that the replication of complex microstructures would be more accurate with COP than with PMMA.

Injection-Compression molding conditions

Preliminary tests were conducted with the two resins, in order to establish a feasible range of injection compression molding parameters which provides a stable process and acceptable parts. It became obvious that even slight deviations in melt and mold temperatures from the settings recommended by the COP supplier resulted in significant warpage or it was difficult to release the part from the mold. No such problems occurred with PMMA. Tables 1a,b list minimum (L), central (C) and maximum (H) values of the processing parameters used for both polymers in the design of experiments. The three temperature values in the melt temperature column are the temperature settings in the barrel, the last one being at the nozzle. The injection velocity column contains two values. The first is the injection piston velocity employed during filling (83 mm injection piston

travel distance), and the second its velocity employed during the holding stage (1mm piston travel distance). In the compression stage columns, the Start parameter stands for the injection piston position with respect to the gate, when compression starts. Thus, a value of 0 indicates that injection and compression are in sequence, while a value other than 0 means that they are carried out in part simultaneously. The compression gap corresponds to the distance travelled by the mobile plate during compression, in order to completely close the mold. This occurs with a velocity V and compression force F . The minimum compression stroke is defined by the mold protection control set to 0.3 mm. When compression gaps higher than 1.5 mm were tested, slight surface defects, possibly due to trapped air, appeared close to the edges of the parts. Therefore, the compression tests were done within a compression gap range of 0.3 to 1.5 mm. The closing velocity V during the compression stage was varied over a wide range, from 1.5 mm/s to 140mm/s, without any visible effect on part quality. Similarly, the full possible range of the clamping force of the press (5 to 50kN) was used, when closing the mold during compression, without causing noticeable surface defects. Tables 1a,b show that five parameters were varied for COP and seven for PMMA. Finally, in order to avoid part deformation at ejection, cooling time, ejection delay time and force were optimized prior to carrying out the full-factorial test plan. Cooling time and ejector delay time were set to 2.5 s and 6 s for COP, while for PMMA they were set to 5 s and 2 s, respectively.

As mentioned above, the preliminary tests showed that PMMA was relatively easy to mold compared to COP. Therefore it was molded first during the final tests. The tests were conducted according to a full-factorial plan with full resolution. In this way, each parameter was unambiguously evaluated, to permit the analysis of the influence of each individual parameter on the transcription of the microstructure. The central point was implemented at the beginning, in the middle and at the end of each test plan. For PMMA, randomization of the runs was omitted, because the adjustment of new barrel or mold temperatures took a long time. Hence, the PMMA experimental plan was divided into four blocks, defined by the settings of the barrel and the mold

temperatures. Since COP appeared to be very sensitive to temperature changes, the variations of the barrel and the mold temperatures were omitted. Consequently the full-factorial test plan contained only five parameters. Except for the magnitudes of the variable parameters, the tests were conducted like the tests with PMMA. However, randomization was easier in this case, because the temperatures were not among the group of examined parameters.

Visualisation and dimensions measurements

Inspection of the transcription of dimensions was based on the measurement of the height or depth of the molded microstructures at specific locations and comparing them to the corresponding measured values for the mold insert. The measurements were carried out using a scanning confocal microscope from Sensofar (PLμ 2300 model). This non-contact optical imaging profiler uses a mapping software to image the surface topography of the observed zone. Since the optical profiler is used in the reflection mode, the samples were sputtered with Pt to improve the naturally low reflection of the transparent polymers. Scanning electron microscopy (SEM) was also used for inspection of the replication quality.

Results and Discussion

A transcription ratio T_R was defined, in order to assess the degree of replication (Ito et al., 2006):

$$T_R = \frac{h_{sample}}{h_{insert}}$$

where h_{sample} and h_{insert} are the measured dimensions of the molded microstructures and the corresponding dimensions measured on the insert, respectively. The measured transcription ratios were used in the statistical analysis of the replication quality, in order to evaluate the significance of the effects. Thus, the statistical analysis displays the standardized effects on the transcription ratio as a bar chart known as the Pareto plot.

Microstructures replication with PMMA

Since the test runs were not randomized, the test plan was divided into four blocks, each block being characterized by different temperature settings for the melt and the mold: Block 1 (low barrel and low mold T), Block 2 (low barrel and high mold T), Block 3 (high barrel and low mold T), Block 4 (high barrel and high mold T). This plan was used to evaluate the effect of temperature on microstructure transcription. Figure 8a shows an SEM image of the micro-channel at location 1 of the insert, while Fig. 8b shows the SEM image of the corresponding microstructure on the molded part. Across the width of this microstructure, two areas having heights of 10.5 and 15 μm can clearly be distinguished. This step across the width is displayed by the trace of the profile obtained by the confocal microscope, which also indicates a maximum replicated height of 15 μm , 5 μm short of the depth of the trench in the insert at that location. This translates into a maximum transcription ratio of 0.75 in this particular example. Figure 9 displays the results of the height measurements for all the 128 test runs with PMMA at location 1, grouped according to the blocks defined previously. The maximum height is measured relative to the left and right adjacent lands, giving two data points for each experiment. Figure 10 shows the corresponding transcription ratio data. The results from blocks 2 and 4 are clearly more stable, with an average transcription ratio of about 0.8. These two blocks were run with the mold temperature set at 'high'. On the other hand, the transcription ratio results for blocks 1 and 3, which were run with the mold temperature set at 'low', varied significantly, depending on the molding conditions. The standard deviation for the low mold temperature case was almost four times the standard deviation for the high mold temperature case. This suggests that reproducibility of the transcription quality will be greater with the hot mold condition. Comparison between the data from block 1 and 2 (low melt temperature) with data from blocks 3 and 4 (high melt temperature) shows a slight improvement in the height replication, when melt temperature is higher. However, it is, clear that the mold temperature had a much more significant effect than the melt temperature. Moreover, higher mold temperature yields a more

stable injection-compression molding process and better replication. Table 2 gives the minimum, maximum and the average height values for each block of experiments along with the corresponding standard deviations, while Fig. 11 shows the Pareto plot derived from the statistical analysis of the data obtained for location 1. The results show that the compression gap is the single most significant parameter (-5.20 %). It has a negative impact on the transcription ratio with a very high probability. This means that the transcription ratio decreases an average of 5.2 % when the compression gap increases from 0.7 to 1.5 mm, which is the low and high limits of this factor for PMMA processing. When the compression gap is large, the travelling distance to mold closure (see figure 2) is longer and therefore, more time is available for the molten polymer in the cavity to cool down with subsequent increase in viscosity. Filling the micro channel upon closure of the mold becomes harder because of the higher flow resistance, lowering the efficiency of the replication. On the other hand, mold temperature, the next single most significant parameter (+4.82 %), has a positive impact on the transcription ratio, also with a very high probability. The positive impact of higher mold temperature is possibly due to delaying or suppressing the frozen layer and facilitating flow inside the micro-channels by keeping viscosity to a low level for a longer time. Other significant impacts are due to injection velocity (-4.81 %) and closing speed (+4.23 %). The respective negative and positive impacts of these two parameters may be also attributed to the time available for the polymer to cool down before total closure of the mold. Tofteberg et al. (2008) discussed the effect of injection speed and mold temperature for the replication of a diffractive optical element using micro-injection molding and both COP and PMMA. They found that the degree of replication increases with both parameters. In particular, the improvement of replication by increased injection speed is due to several factors, among them reduced viscosity due to shear thinning and shear heating, but also less cooling of the polymer before reaching the mold wall and faster pressure build-up at the wall which will enhance the flow into the microcavities. However, their argument cannot be used for the case of the injection compression process because the mold is

not totally closed during injection, where shear heating and thinning take place and where pressure in the cavity is obviously low. For a constant mold closure speed, the higher the injection speed the more cooling time is available to the melt. By the time pressure is built up by compression during mold closure the polymer viscosity would have increased substantially, erasing the benefit of shear thinning and heating. This may explain the negative effect of increased injection speed. On the other hand, for a constant injection speed, increasing the mold closure speed will reduce the available cooling time before pressure build-up and a better replication would result. The least significant factor (+0.54 %) appears to be the compression start (CS) parameter which seems to indicate that the relative position of the injection piston when compression starts did not play a big role in this particular case. However, when the CS factor is high, the compression starts early, before full injection is ended, and less cooling would take place, which explains the positive impact, however small, of this parameter. The results from the Pareto plot of Fig. 11 suggest that all significant interactions effects between the process parameters are somehow associated with the mold temperature, with the exception of the interaction between the compression gap and the closing speed. The plot indicates, for example, that the effect of mold temperature associated with higher injection speed settings results in an improvement of the transcription ratio by about 5.1 %. This can be possibly explained by the viscous dissipation generated by very high shear rates generally encountered in micro-molding, especially when injection speed is high.

Microstructures replication with COP

For the COP resin, the factorial plan was randomized and consisted of 32 experimental runs. Mold and melt temperatures were not changed. They were kept constant at the values given in Table 1. Microstructure replication at location 2 (see Fig. 5) was also analyzed using both COP and PMMA. Figure 12 displays the SEM micrographs for both resins. As opposed to location 1, the overall replication seems to be more homogeneous and smooth, as no step is observed in the transcription

at location 2. Figure 13 shows the corresponding transcription ratios at the maximum height achieved for each run, across one of the arms of the cross-shaped microstructure. A higher transcription ratio, with an average value of 0.9, was achieved with COP, compared to PMMA. Figure 14 displays the Pareto plots obtained for both COP and PMMA at location 2. The results for COP show that the compression force was the single most significant parameter with a positive impact on the transcription ratio of 6.0 %, as compared to the PMMA case with only a 3% positive impact. The compression gap had a much less negatively significant (-3.1 %) for COP than for PMMA (-15.8%), while the injection speed was surprisingly positively significant (+2.5 %) for COP as opposed to PMMA (-4.8%). The mold closing speed during compression had opposite impacts on the transcription ratio. A higher closing speed was needed with PMMA than with COP. The differences in the results obtained for both resins may be attributed to the time available for cooling and to their respective viscosities. If a molding parameter reduces the amount of cooling during the transcription process, it will have a more positive impact on the microstructure replication. As shown in Figure 7, COP has less flow resistance at its processing temperature range than PMMA which should translate into better replication.

Figure 15 shows the SEM-pictures of the microstructure at location 4 for the mold insert and for parts molded from both materials. They show that the cylindrical pillars on the parts molded from COP exhibit slightly better transcription quality, with almost no surface defects compared to those molded from PMMA. A similar observation can be made for the square shaped pillars. In both cases, however, the transcription ratios were found to be low, with values between 0.5 to 0.6, compared to those previously discussed for locations 1 and 2.

Conclusions

Micro-injection compression tests were conducted, using PMMA and COP, to investigate the effects of processing parameters and their possible interactions on the replication quality of surface

microstructures. For PMMA, it was found that higher mold temperature was most beneficial for transcription quality. The impact of melt temperature was less significant. For COP, the temperature effect was not investigated, due to the high sensitivity of this polymer to temperature change. However, it was found that the compression force had the most significant positive impact, followed by injection speed. For both resins, compression gap had a negative impact on the transcription ratio. Therefore, it should be kept as small as possible. Furthermore, COP shows a higher capacity to transcribe structures in the μm -range, due to its better ability to flow.

Acknowledgements

The authors acknowledge the support of the National Research Council of Canada and would like to thank Normand Nardini from the Industrial Materials Institute (IMI) for his constant help in conducting the experimental tests.

References

- Chen, C.-C.A., Kao, S.-C., "A study of two-stage micro injection compression molding process for diffractive optical lens", *Key Engineering Materials*, **364-366**, 1211-1214 (2008)
- Chien, R.-D., "Micromolding of bioship devices designed with microchannels", *Sensors and Actuators A: Physical*, **A 128**, 238-247 (2006)
- Guo, J., et al. "Study of the Demolding Process – Implication of Thermal Stress, Adhesion and Friction Control", *J. Micromech. Microeng.*, **17**, 9-19 (2007)
- Heckele, M., Schomburg, W.K. "Review on micro molding of thermoplastics ", *Micromech. Microeng.*, **14**, R1-R14 (2004)
- Hetu, J.F. et al. "Three dimensional simulation of injection molding of parts with microstructures", *AICHE 2005 Annual Meeting, Cincinnati*, Paper ID31792 (2005)

Ito, H. et al. "Development of a novel Transcription Molding Process to fabricate Sophisticated Polymer Products with precise Microstructure and high Transparency applicable to Display Devices and Bio-Chips", *Int. Polym. Proc.*, **XXII**, 2, 155-165 (2006)

Shen, Y.K., et al. "Study on Optical Properties of Microstructure Lightguiding Plate for Micro Injection Molding and Micro Injection-Compression Molding", *Materials Science Forum Vols. 505-507*, 229-234 (2006)

Shen, Y.K. "Comparison of height replication properties of micro-injection moulding and micro-injection-compression moulding for production of microstructures on lightguiding plates", *Plastics, Rubber and Composites*, **36**, 77-84 (2007)

Su, Y.-C., et al. "Implementation and Analysis of Polymeric Microstructure Replication by Micro Injection Molding", *J. Micromech. Microeng.*, **14**, 415-422 (2004)

Tofteberg, T. et al. "Injection Molding of a Diffractive Optical Element", *Polym. Eng. Sci.*, **48**, 11, 2134-2142 (2008)

Tseng, S.C., Liao, C.L. "A Study of Processing Conditions on the Properties of Diffraction Optical Elements by Injection/Compression Molding Process", *Int. Polym. Proc.*, **XVIII**, 2, 194-198 (2003)

Turng, L.-S. "Special and Emerging Injection Molding Processes", *J. Inj. Mold. Tech.*, **3**, 160-179 (2001)

Wimberger-Friedl, R. et al. "Molding of microstructures and high aspect ratio features", *SPE ANTEC*, 539-543 (2003)

Wu, C.-H., Chen, W.-S. "Injection Molding and injection compression molding of three-beam grating of DVD pickup lens", *Sensors and Actuators A: Physical*, **A 125**, 367-375 (2006)

Yu, L. et al. "Flow and Heat Transfer Simulation of Thin-Wall Injection Molding with Microstructures", *SPE ANTEC*, 602-606 (2003)

Zhao, J. et al. "Effect of Process Parameters on the Micro Molding Process", *Polym. Eng. Sci.*, **43**, 9, 1542-1554 (2003)

Melt temperature [°C]		Mold temperature [°C]	Injection velocity [mm/s]	Compression Stage			
				Start [mm]	Gap [mm]	Velocity [mm/s]	Force [kN]
L	215 – 230 – 235	65	100 – 4.3	0	0.7	1.5	5
C	217 – 232 – 238	70	500 – 21	300	1.1	70.7	27.5
H	220 – 235 – 240	75	900 – 39	600	1.5	140	50

Table 1a – Experimental Processing Parameters - PMMA

Melt temperature [°C]		Mold temperature [°C]	Injection velocity [mm/s]	Compression Stage			
				Start [mm]	Gap [mm]	Velocity [mm/s]	Force [kN]
L	265 – 270 – 280	60 – 60	400 – 17	0	0.3	1.5	5
C			650 – 28	360	0.4	70.7	27.5
H			900 – 39	720	0.5	140	50

Table 1b – Experimental Processing Parameters – COP

	Minimum value [μm]	Maximum value [μm]	Average value [μm]	Standard deviation [μm]
Complete test plan	10.28	18.31	15.34	1.61

Block 1	10.28	17.84	14.49	2.18
Block 2	14.33	16.81	15.71	0.66
Block 3	11.79	18.31	15.20	2.05
Block 4	14.83	17.23	15.82	0.57
Block 1 & 2	10.28	17.84	15.11	1.70
Block 3 & 4	11.79	18.31	15.51	1.52

Table 2 - Range of variation, average values and the standard deviation of the heights, PMMA, insert 2 location 1

Figure 1 – a) SEM micrographs showing as molded microstructures c) 3D simulation prediction of temperature distribution at end of packing. (Ref. [2])

Figure 2: Illustration of the injection compression molding process

Figure 3 – Battenfeld Microsystem 50 press with a schematic showing the plastication, metering and injection units

Figure 4 – Representation of silicon wafer master with 7 different schematic patterned zones

Figure 5 – Schematic details of microstructures from insert used (zone 2 in Figure 4)

Figure 7 - Viscosity vs. shear rate of COP Zeonor 1060R and PMMA M30 at processing temperatures.

Figure 8 - SEM images of a) insert and b) molded microstructure (PMMA) along with c) the profile at location 1; L: height with respect to left land, R: height with respect to right land.

Figure 9 – Maximum replicated height - PMMA, location 1

Figure 10 – Transcription ratio vs. experimental runs - PMMA, location 1

Figure 11 – Pareto plot: Effect of the various molding parameters, PMMA, location 1

Figure 12 – SEM images of insert and molded microstructures using COP and PMMA

Figure 13 – Transcription ratio vs. experimental runs – PMMA (top) and COP (bottom), location 2

a) PMMA

b) COP

Figure 14 – Pareto plot – a) PMMA and b) COP, location 2

Figure 15 – SEM images of a) insert and molded microstructure b) (PMMA) and c) (COP), location 4