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ZERO DEFECTS MANUFACTURING IN INJECTION COMPRESSION MOLDING OF POLYMER FRESNEL LENSES

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Abstract

Fresnel lenses are polymer optics with reduced dimensions and higher illumination properties. Their structured profile involves high precision replication techniques when industrial scale manufacturing is concerned. Injection Compression Molding (ICM) is the state of the art replication technology to ensure mass production of polymer optics. The opportunity to perform a compression phase on the polymer melt while injected into the cavity, ensures a more homogenous replication of the part, enhancing birefringence and transparency among all the optical properties. However, it is not common to find studies concerning the technological signature of ICM components. The optical transparency of polymer optics as long as the complexity of Fresnel lens profile, are big challenges for metrology making this knowledge expensive and rarely investigated. In this study, absolute dimensions of Fresnel lenses step heights are correlated with respect to ICM process conditions. In a first experimental plan, the effect of packing and compression is individually evaluated on two different materials. In the case compression is performed without packing, the form replication accuracy of the micro structures fails, showing deviations up to 10 times the nominal dimension. On a secondary experimental campaign, packing pressure and compression gap are optimized together to identify the most favorable replication condition. The results show a second order interaction between compression gap and packing pressure. The average replication increases by 1.4 %, 2 µm, when both a high level of compression gap and packing pressure are selected.

Introduction

Fresnel lenses are nowadays a very well-known optical solution and product. The segmented design of these lenses allows, in many circumstances, to lower the lens thickness, to reduce spherical aberration and to enhance light transmission. Especially for these reasons, Fresnel lenses are extensively used in automotive, electronics, indoor and outdoor lighting and solar energy industries.

Considering the complexity and the high density of features of the Fresnel pattern, mass production of these products involves high precision and accuracy manufacturing technologies. As far as polymer optics are concerned, replication processes represent the best fit for the purpose. Replication technologies exploit a master mold, answering specific hardness and fatigue resistance requirements, to reproduce a plastic or polymer sample [1].

Injection Compression Molding (ICM) is the leading process technology for mass manufacturing of high precision polymer optics. The process leads to high accuracy replication of micro structures and surface finishing suitable for optical applications [2].

The injection compression technology is a natural extension of the traditional Injection Molding (IM). The difference consists in the compression phase.

In IM, polymer melt flows following the constraints, which are given by the cavity geometry. On the other hand, in ICM, compression, which consists of a normal force acting on the melt, breaks the geometrical dependency of the flow and allows a more homogeneous polymer chains redistribution inside the cavity. The compression stroke is namely known as compression gap and plays a significant role in ICM process control [6].

The use of ICM leads to multiple optical advantages. One of them consists in the improvement on birefringence properties [3]. When compression is performed, the distribution of polymer chains does not follow the cavity geometry, reducing the dependency of the refraction index with respect to the light propagation direction. Birefringence in the part can be simulated and it is proved to lower down in the case ICM is preferred to IM during polymer Fresnel lenses production [4].

Another optical advantage that can be achieved by ICM is represented by the lower deformation of the wavefront passing through the lenses, which consists in an overall reduction of the optical aberrations with respect to IM [5].

When ICM performances are evaluated, one important aspect that should be also considered is the gate location and the part design. Both the distance and the position of the gate with respect to the part represents a factor significance when both optical properties and polymer replication are concerned [6, 7].

Even though the advantages of the optical functionality were extensively studied, it is hard to find references on ICM technological signature, i.e. the geometrical replication fidelity of micro structures produced by ICM. The biggest challenges that limit this field of research, are the metrological challenges, which for the case of Fresnel lenses are the transparency, the required accuracy, the multiscale of the 3D micro structured profile and the overall metrological costs.

The goal of this research is to provide a deeper understanding of the replication behavior in precision ICM of polymer Fresnel lenses, considering the technological signature of ICM as the micro structures of the lens profiles.

Materials

Two optical grade transparent amorphous polymer materials are selected for the experimental campaign. Firstly, a Cyclo Olefin Polymer (COP) is chosen. COP polymer was manufactured by ZEON company.

Secondly, a Poly-Methyl Methacrylate (PMMA) is considered. This polymer was produced by ARKEMA company. Both the polymer materials are used for optical applications thanks to their low water absorption, transparency and optical performances [8, 9].

In Table 1, are reported the physical properties of the two polymers. The similar volumetric shrinkage allows adopting the same cavity design when molding a material or the other. COP is lighter with respect to PMMA if we look at the density.

On the contrary, as shown in Figure 1, the viscosity of COP is higher for both the selected melting temperatures. The rheological properties come from Autodesk© Moldflow material default database.

The slope of the curves indicates that COP has a more continuous reduction of viscosity when the shear rate is increased. PMMA instead, has a constant viscosity until a shear rate of 100 1/s is reached, at this point viscosity converges to the same values independently from the melt temperature.

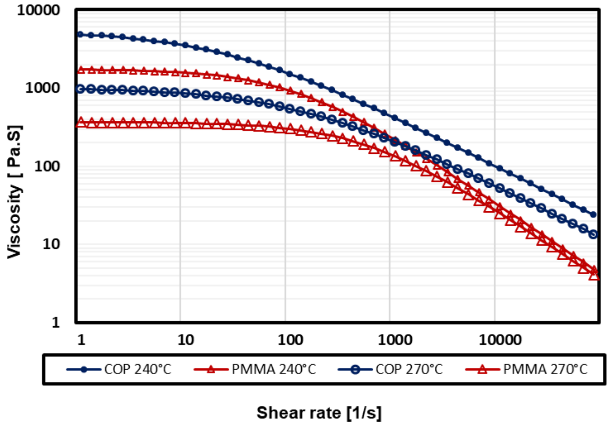


Figure 1: Viscosity against shear rate for COP and PMMA

Table 1: Physical properties of COP and PMMA

	Method	COP	PMMA
Density	ISO 1183	1.01g/cm^3	1.19 g/cm^3
Shrinkage	ASTM D955	0.5-0.7 %	0.4-0.6 %

Fresnel lens design

The experimentation is performed on a Fresnel lens design following the specification of the automotive industry. The profile is applied on a rectangular solid base of dimension 85 mm x 60 mm and 2 mm in thickness, as shown in Figure 2 (a).

The Fresnel pattern covers a squared portion of 40.2 mm x 40.2 mm. The center of the lens is aligned in the y-direction with the runner and it is centered in the mold in the x-direction.

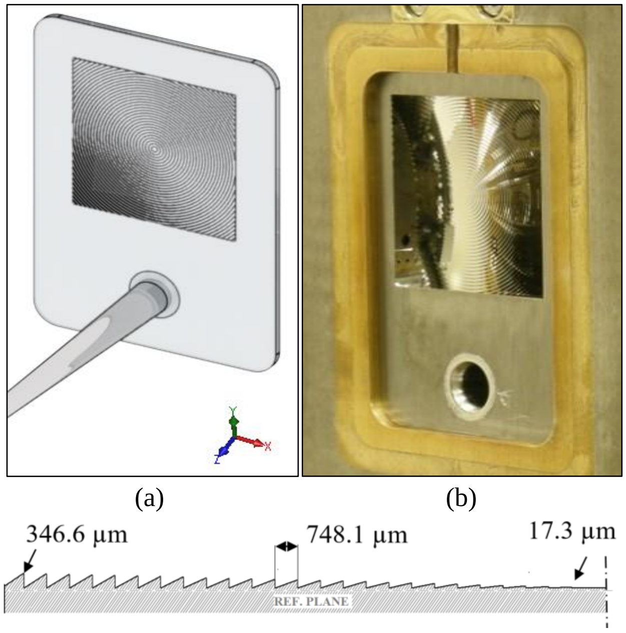
The micro structures consist of 52 complete concentric grooves distanced by a constant pitch of 748.1 µm. Those have a triangular cross-section, whose bottom side lies on the base rectangular part where a reference plane is located.

As shown in Figure 2 (c) from the reference plane to the top edge of each groove, the step height ranges from a minimum of 17.3 µm in the lens center to a maximum of 346.6 µm in the outer regions. The aspect ratio of the features is low and it ranges from 0.02 to 0.46.

Injection compression molding equipment

Injection compression molding is performed with a commercial machine made by Negri Bossi. The molds design answer optical quality. A toggle clamp with two plates mold is equipped on the machine. The mold is improved by means of two conical interlock to align the fixed side plates together. On the movable side, a hydraulic actuator connected to the ejection plate enables the displacement of three ejection pins for automatic demolding.

In order to ensure the control of the compression gap,



(a) (b)

(c)

Figure 2. CAD model (a) and the cavity design (b) with the highlight of the Fresnel section profile design (c)

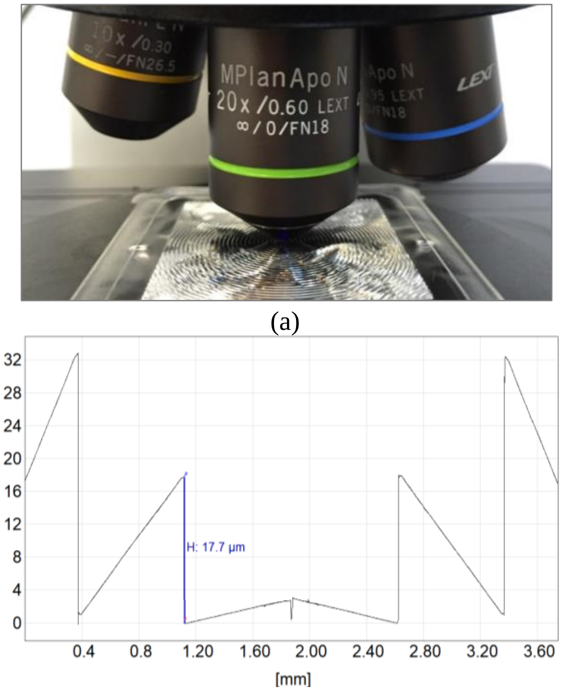
the toggle unit displacement is calibrated by direct comparison of the measured clearance between the molds and the position of the toggle head unit. A regression model shows a linear relationship between the two factors with an R^2 of 99.8 % calculated on 9 different points replicated for 3 times. In this way, it was possible to control the compression gap in the subsequent Design Of Experiment (DOE) by controlling the toggle head unit position.

The insert geometry, represented in Figure 2 (b), is produced in Nickel with an electroforming process chain. Which means an initial machining of the final geometry on an aluminum master by diamond cutting. Afterwards, Nickel is electroformed on the master. The further step consists of selective etching of the aluminum to release a pure Nickel insert. At last, precision machining ensures the tolerances of the insert back for molding purposes. This process chain ensures high replication accuracy of the parts, with calculated deviation from nominal dimensions for form geometries < 20 nm [10].

A venting channel is put on top of the insert cavity and promotes air evacuation during replication.

Measuring strategy

In order to assess the technological signature of ICM micro structures of the Fresnel lens profile, a laser scanning confocal microscope from Olympus company is adopted. As shown in Figure 3 (a), the working distance of the microscope is 1 mm while the measured profile (b) has a minimum step height of 17.7 µm.



(a)

(b)

Figure 3: Measuring the step height with a confocal microscope (a) and the resulting Fresnel lens profile (b)

The microscope allows a vertical resolution below 30 nm on the form geometry and a calibration of the metrological routine on 10 repeated measures indicates an uncertainty of 100 nm on the measured step height.

Experiments

The experimental campaign follows DOE procedure. The analysis is implemented to address the replication quality of four different process conditions for the two materials, consisting of a full factorial design with 3 factors on two levels.

Two different process replicates are measured after 10 complete cycles for a total of 20 molded parts per process condition. 16 samples are then inspected in the DOE. The experiment is reported in Table 2. In this experiment, compression is controlled by a compression gap of 1.0 mm, while packing pressure is fixed at 250 bar.

After this preliminary study, ICM process parameters are optimized in another DOE. In this case, a 2^2 full factorial design analyzes the interaction between compression gap (0.4 – 1.0 mm) and packing pressure (250 - 450 bar). This experiment is conducted only for COP. Two process replicates per DOE line are considered for 8 total analyzed samples. The experimental plan is shown in Table 3.

For both DOEs, the other most important IM parameters are not varied during the experiments: melt temperature is 240°C, mold temperature 107 °C, clamping force 650 kN and injection velocity to 40 mm/s.

The results are sampled at two locations (left-right) at the same distance from the gate. This doubles the number of results considering a location factor.

Table 2: DOE investigating the effect of *Compression*, *Packing* and *Material*

Run	**Compression**	**Packing**	**Material**
1	OFF (-)	OFF (-)	COP (-)
2	ON (+)	OFF (-)	COP (-)
3	OFF (-)	ON (+)	COP (-)
4	ON (+)	ON (+)	COP (-)
5	OFF (-)	OFF (-)	PMMA (+)
6	ON (+)	OFF (-)	PMMA (+)
7	OFF (-)	ON (+)	PMMA (+)
8	ON (+)	ON (+)	PMMA (+)

Table 3: DOE assessing Compression Gap and Packing Pressure interactions

Run	**Compression Gap [mm]**	**Packing Pressure [bar]**
1	0.4 (-)	250 (-)
2	1.0 (+)	450 (-)
3	0.4 (-)	250 (-)
4	1.0 (+)	450 (-)

Discussion

The results of the first DOE consists of main effects plot of the averaged data sample in Figure 4. The graph suggests an average higher replication with respect to the nominal value. PMMA shows a higher step height replication and this phenomenon is addressed to the lower viscosity with respect to COP at the operating conditions. Location factor does not have a strong significance on the replication effects, while packing and compression do play a role.

The presence of a packing phase increases the replication. This is normal for IM and ICM because it compensates shrinkage while the part cools down after the cavity is filled.

Compression instead has a negative effect on the average replication of the part. A deeper data analysis shows that for the 6th DOE run, the case in which packing is OFF and compression is ON in PMMA the replication of the part fails.

As represented in Figure 5 (a) the part is subjected to a large deformation with respect to a case where both packing and compression are performed (8th run) and the deviations in the form geometry are over a factor 10. This phenomenon is addressed to air trap.

In ICM, to allow the compression of the polymer melt, the cavity is initially larger and contains a higher air volume inside, which needs to be expelled before the part solidifies.

The fact that the air trap occurs only for one polymer material, suggests that this issue is not bounded only by venting or mold design; nevertheless, it should also depend on the material properties. Moreover, this condition justifies why compression effect drops down the average replication results.

Starting from this point, the optimization of the packing phase with respect to compression gap aims to identify a zero defects and the optimized ICM process conditions.

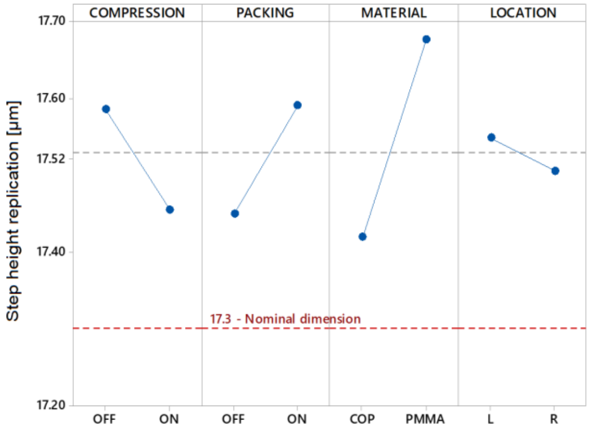
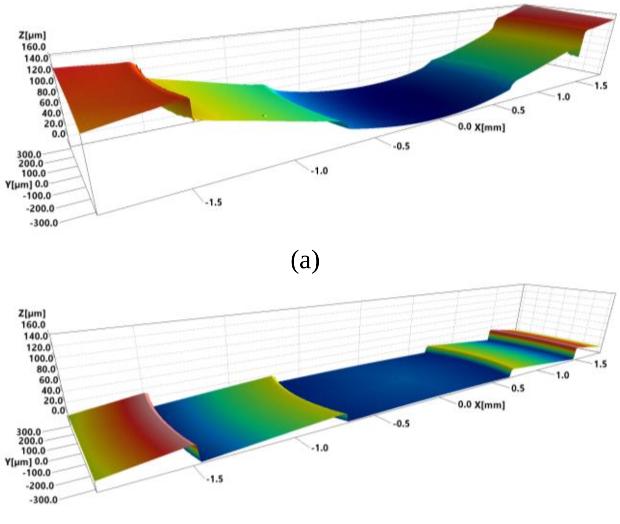


Figure 4: Main effects plot of the average step height replication



(a)

(b)

Figure 5: Replication failure (a) and full replication (b) of the central region of the Fresnel lens.

The second experimental campaign confirms this hypothesis. The results are now expressed in terms of replication percentage of the nominal dimension. In Figure 6, data are individually plotted. The new dataset is sampled on a higher groove of the lens with a nominal step height of 132.2 µm. The main effect plot of step height replication % for the COP material, shown in Figure 7 (a), indicates that a high packing pressure level of 450 bar increases the average replication by 1.4%, equivalent to 1.9 ± 0.1 µm.

Despite a smaller compression gap, 0.4 mm, increases the average replication, the interaction plot of Figure 7 (b) shows that the best replication condition is achieved when the gap is at the high level, 1.0 mm, with a packing pressure of 450 bar.

The influence of gate location does not show a significative effect on the averages both in the main effect and the interaction plot. This demonstrates replication stability in the longitudinal direction of the melt propagation flow.

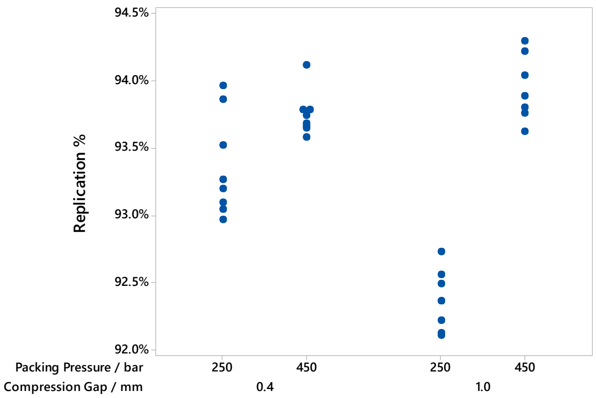
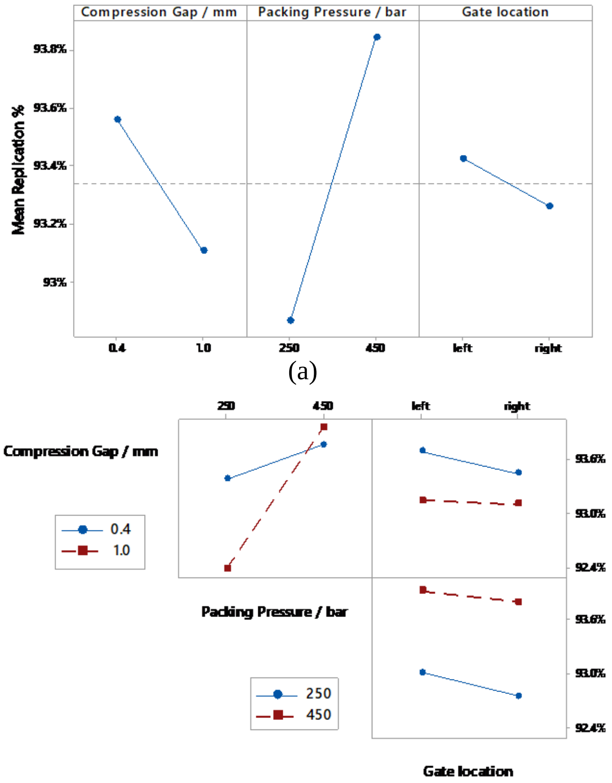


Figure 6: Individual value plot of replication % of the Fresnel lens step height



(a)

(b)

Figure 7: Main effects plot (a) and interactions plot (b) of the replication % of Fresnel lens step height

Conclusions

In the current work, micro structures replication fidelity on a Fresnel lens profile is evaluated. In this context, an approach based on the technological signature of ICM to achieve zero defects manufacturing is proposed.

Confocal microscopy allows measuring step height absolute dimension of the transparent, micro structures of the optical parts-.

A replication failure condition is observed when only compression and no packing is performed on the part. The reason for the failure is addressed to the lack of air trap compensation or expulsion generally resolved by packing and worsen by the higher air volume brought in the cavity due to compression.

In order to achieve enhanced replication accuracy in ICM, packing pressure and compression gap needs to be controlled and optimized together because their second-order interaction has a significative effect on the average response.

Replication is constant in the longitudinal direction of the melt flow front as long as two positions, i.e. left and right, are concerned at the same gate distance on a direction which is longitudinal to the melt flow propagation.

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