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Comparison of Injection Molding Technologies for the Production of Micro-Optical Devices

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Abstract

Injection molding is a complex process regulated by many factors (injection speed, injection pressure, melt temperature, mold temperature, and others). Despite, process control and parameter optimization, it is often difficult to replicate thermoplastic components with adequate dimensional accuracy, especially in the case of geometries with high aspect ratios. For these reason, there is a need for innovative moulding technologies such as Injection Compression Molding – ICM or Vacuum Injection Moulding – VIM. In this paper conventional injection molding – IM is compared to ICM and VIM for the replication of optical thermoplastic microscale prism patterns typical of Fresnel lenses. A full Design of Experiments was performed including several micro structured prism geometries, injection molding technologies and specific process parameters for a total of 288 tests. Data analysis evidenced the greater quality of workpieces obtained by ICM, whereas VIM was a minor process improvement.

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Keywords: injection molding; injection compression molding; vacuum injection molding; accuracy

1. Introduction

The recent innovations in telecommunications, photovoltaic technology, medical imaging-diagnostics, surveillance systems and illumination systems strongly enhanced the interest in manufacturing complex-shape optic components whose dimensions are in the range from 10 μm to 100 μm , commonly named micro-optics or MesoOptics.

The main processes available for massive production of MesoOptics are hot embossing, used to produce micro structured plastic films (holograms, wearable reflex, retro reflectors for street application, and others), and injection

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molding, applied to produce tridimensional optical components (compact optics for CCD, micro-diffusers, Fresnel lenses, and other [1]). At the present time, only injection molding is economical for mass production due to its high productivity [2]. The efficiency of these techniques for manufacturing micro-optics is very limited and there is a strong need for innovative instrumentation and manufacturing methodologies. Moreover, the dimensional accuracy required by optical components is high and it is often difficult to achieve the required quality standards.

The injection molding process at micro scale is very complex and there are many factors which influence the process such as: injection speed, injection pressure, melt temperature, mold temperature, and others [3]. There are strong interactions among process parameters, variation of process conditions and other possible phenomena (for instance, air traps) which reduce process repeatability. Therefore, advanced technologies (e.g. adaptive injection moulding, pulsed cooling technology, ultra-high speed injection moulding, and others) have been developed. Generally, it is not always possible to improve the process accuracy simply by regulating process parameters or by minor modifications of the mould or of the production set-up. These aspects are of particular relevance when the molded component is an optical device, which requires both high dimensional accuracy and surface quality.

In this paper, conventional injection molding – IM is compared to two innovative methodologies such as Injection Compression Molding – ICM and Vacuum Injection Molding – VIM for the replication of optical thermoplastic micro scale prism patterns typical of Fresnel lenses. Recent publications dealing with this topic are first discussed, then the experimental procedure is described in detail. Eventually, the experimental data is discussed and conclusions are drawn.

1.1. State of the art

In Table 1, recent scientific publications dealing with innovative injection molding techniques and investigating the effect of injection molding parameters are given.

Table 1. Summary of recent research works dealing with injection molding of optical components

Shape	Type	Material(*)	Technology (**)	Main aspects	Ref.	Year
Disc part	2D	PS	IM, ICM	Simulation of injection molding process	[4]	2000
Sample part, plate	2D	PC	IM, ICM	Optical quality obtained by different injection molding processes	[5]	2000
Mono-spherical lens, disk	2D	PC	IM	Effect of the molding conditions on surface contour Errors	[6]	2001
Light guide (wedge shaped)*	2D	PMMA	IM, ICM	Influence of process parameters on shrinkage	[7]	2003
Optical Disc	2D	PC	ICM	Simulation of injection molding process	[8]	2003
Pickup Lens	3D	PMMA	ICM	Simulation of injection molding process	[9]	2005
Pickup lens with diffraction gratings	3D	PMMA	IM, ICM	Comparison of processes for production on diffraction grating	[10]	2005
Plate with V grooves 50 μm	2D	PMMA	IM, VIM	Transcription Ratio for various IM processes	[11]	2006
Optical disc	2D	PS	IM, ICM	Simulation of injection molding process	[12]	2007
Lens with diffractive optical elements	2D	PC, HFP-TFE-Et	IM, VIM	Replication accuracy and optimization for different materials	[13]	2007
Thick walled lens	3D	-	IM, ICM	Geometrical accuracy and optical quality obtained by different injection molding processes	[14]	2007
Plate with V grooves 50 μm	2D	PC	IM	Investigation on transcription accuracy and optical performances for different materials	[15]	2008
Optical lens	2D	PS	ICM	3D process simulation	[16]	2012

(*)PS = polystyrene; PC = polycarbonate; COC = cyclic-olefin-copolymer; PMMA = poly-methyl-methacrylate; SAN = styrene acrylonitrile copolymer; HFP-TFE-Et = hexafluoropropylene-tetrafluoroethylene-ethylene terpolymer.

(**) IM = injection molding; ICM = injection compression molding; VIM = vacuum injection moulding; HE = hot embossing (various).

The table is organized to indicate the component shape, dimensions, material, applied injection molding technologies, main aspects investigated, bibliographic reference and year.

It can be seen that most of scientific works focused on the replication of 2D disc components (disk parts and optical disks). In these applications, strong variations of the thermodynamic conditions of the melt prevent efficient application when the aspect ratio of the component is high. A limited number of publications which investigated 3D optical components such as lenses. Shrinkage and internal stresses are the main problems limiting the dimensional accuracy and quality of three dimensional components.

There are several research works where conventional injection molding is compared either to injection compression molding or vacuum injection molding. Generally, the accuracy obtained by ICM is higher than conventional molding [5][7][10][14]. Also, there are encouraging results when vacuum injection molding is compared to conventional injection molding [11][13]. In none of the publications there is a complete comparison between the three processes and the results are very specific for the considered application.

Many works investigated the process control and the influence of thermo dynamical conditions on shrinkage, residual stresses and birefringence by means of computer simulations. As a general conclusion, the reliability of the results obtained by computer simulation is strongly affected by local transient effects. Therefore, it is very important to validate the results of numerical simulation with laboratory testing [17].

2. Experimental procedures

The reference geometry of the optical prism patterns considered in this research is given in Figure 1. The optical pattern consisted of saw-tooth grooves defined by the following geometrical parameters: prism height H_m , prism angle α and draft angle β . Due to process limits, the thermoplastic do not fill the stamper groove completely. Thus the prism top is smoothed and the achieved prism height H is lower than the height of the grooves in the stamper H_m . The optical efficiency of the prism can be quantitatively characterized by the Transcription Ratio index introduced by Yokoi et al. in 2006 [11]. The Transcription Ratio – TR is the ratio between the actual height of the prism H and H_m , as shown in Figure 1 and equation (1).

$$TR = \frac{H}{H_m} \% \quad (1)$$

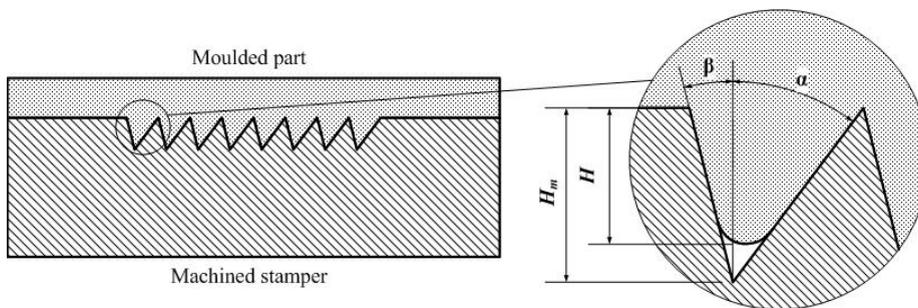


Fig. 1. Geometry of the microscale optical prism pattern

Six prism geometries have been used as tests geometries, as reported in Table 2. These geometries have been selected since they are the basis for micro-optical flat lenses such as Fresnel lenses.

Machined prism features are shown in Table 2. The draft angle β was 2 degrees for all prism geometries.

The prism geometries have been machined on a 50x15 mm 60-40 brass molding insert by single point turning with diamond tools on a Moore Nanotech 250 UPL Lathe. Different cutting tools with different nose radius were applied to machine the prism grooves. SEM inspection was adopted to verify the accuracy of the machine mold inserts and evaluate the maximum achievable prism heights H_m , as shown in Figure 2.

Table 2. Investigated prism geometries

Geometry code	Prism	
	Prism angle α [deg]	Height H_m [μm]
P1	60	100
P2	60	141
P3	45	240
P4	30	426
P5	30	368
P6	30	221

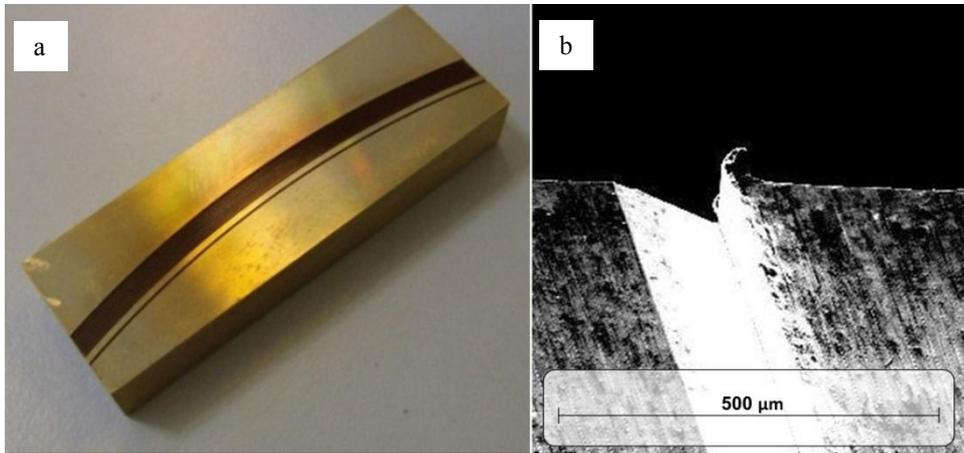


Fig.2.(a) example of micromachined mould insert and (b) SEM inspection of a machined groove

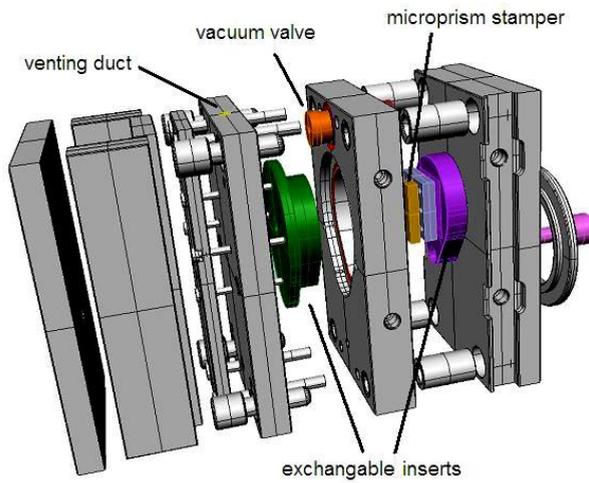


Fig.3.3D representation of the mould design

The polymer selected for the application was Altuglas PMMA V825 T, a commonly used PMMA grade for automotive lighting optical parts. The moulding press was a Negri Bossi VE 70 (maximum clamping force 70 tons.; maximum injection speed: 80 mm/s; max. injection pressure: 190 MPa; max. holding pressure: 150 MPa), compatible with ICM.

A prototype mould compatible with the three injection molding methodologies and composed of exchangeable inserts was designed and manufactured, as shown in Figure 3 and 4. Micromachined brass stampers were clamped to a movable platen insert (see Figure 4) in order to easily modify cavity configuration and change prism geometry.

Toggle movements were used to regulate the compression stroke for ICM.

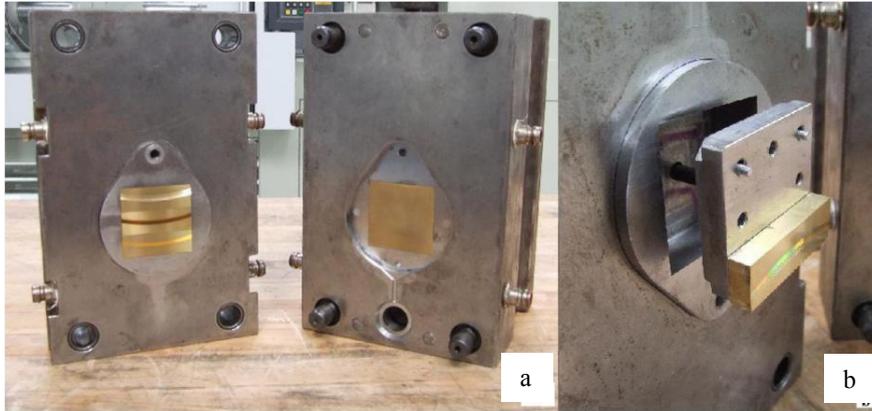


Fig.4. Mould platens (a) and quick change stamper device (b)

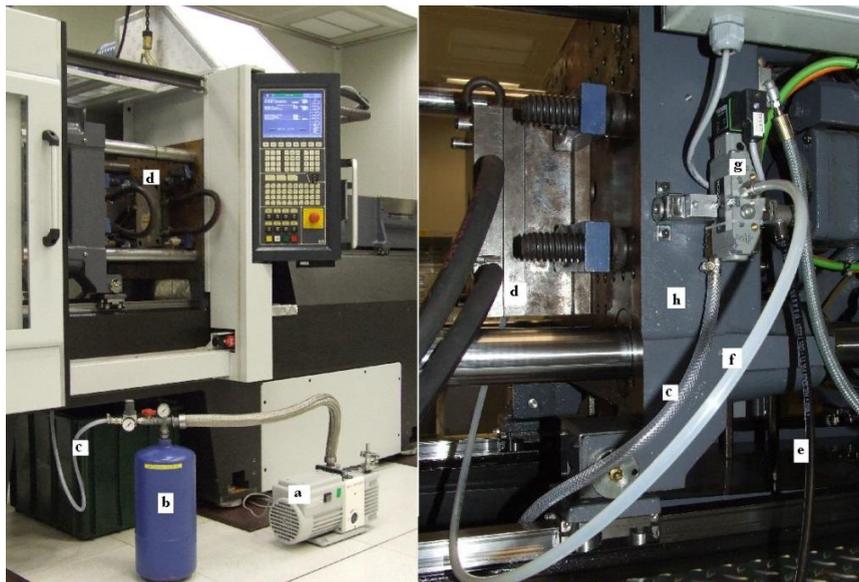


Fig.5. VIM apparatus: a) vacuum pump; b) vacuum tank; c) vacuum line; d) mould; e) compressed air line; f) valve-mould duct; g) three-way valve; h) moving plate

Vacuum apparatus for VIM is shown in Figure 5. The vacuum device was based on a three-way valve – connected to mould cavity, vacuum line and compressed air line - which controlled the mold cavity condition. O-rings were applied inside the mould.

After mould closure, the three-way valve connected the mould to the vacuum line. Vacuum was applied indirectly, using a vacuum tank, subjected to a continuous pumping action by a vacuum pump. When the pressure inside the mould cavity was lower than 0.1 bar, the injection was started. The vacuum venting was held until the cavity was completely filled using an automatic vacuum valve positioned inside the mould. The flow of compressed air was used for de-moulding of the part and to clean the vacuum valve at the end of the moulding cycle.

The VM cycle time was longer (roughly 10 seconds) than IM and ICM cycles due to the time required to reach vacuum condition inside the mould cavity. However, the time could be easily reduced using larger vacuum reservoirs.

Verification of the dimensional correctness of the main mould geometries (sprue, gate, cooling ducts) and selection of suitable ranges of process parameters for each injection moulding methodology were based on MoldFlow CAE software simulations.

In accordance to the results of the CAE analysis, literature review and experience, a design of experiments with three process parameters as factors was realized for each injection molding methodology, as shown in Table 3 and Table 4.

Table 3. Design of experiments of process parameters

Technology	Factor 1		Factor 2		Factor 3	
	Low(-1)	High(+1)	Low(-1)	High(+1)	Low(-1)	High(+1)
IM	Mould temperature [°C]		Holding pressure [bar]		Injection speed [mm/sec]	
	90	100	300	1000	30	70
ICM	Injection pressure [bar]		Holding pressure [bar]		Compression gap [mm]	
	500	1000	500	900	0.6	1.5
VIM	Injection pressure [bar]		Holding pressure [bar]		Injection speed [mm/sec]	
	600	1600	300	800	30	70

Table 4. Investigated prism geometries

Factor	Levels
Injection molding methodology	3
Prism geometry	6
Factor 1	2
Factor 2	2
Factor 3	2
Repetitions	2
Total tests	3x6x2x2x2x2 = 288

Each sample was inspected using a Veeco Sloan Dektak 3 ST contact profilometer with stylus tip radius 2,5 µm, inspection length 4500 µm, contact force 30 mg, point density 0.625 µm/point, Figure 6 a). An example of digital profile obtained from profilometer inspection is given in Figure 6 b).

Digitalized profiles were elaborated in Matlab to determine the transcription ratio TR for each peak and stored in a database for statistical analysis.

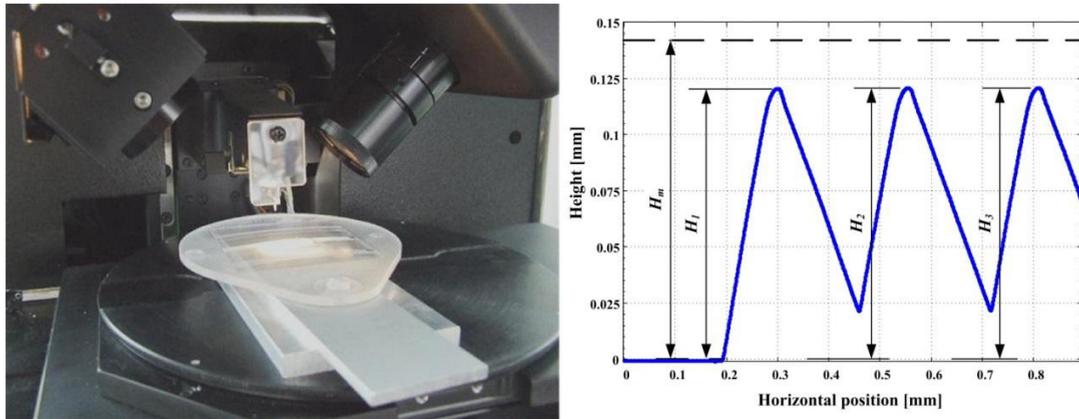


Fig.6.a) Profilometer and measuring configuration; b) example of moulded part measurement

3. Data analysis and discussion

The boxplots of the transcription ratio for the injection moulding methodologies and for each prism geometry are given in Figure 7. Ideally, the average point represented by the red line inside the boxplot should be as close as possible to 100% – for accuracy – and the vertical dimension of the box – which is related to dispersion/precision – should be small.

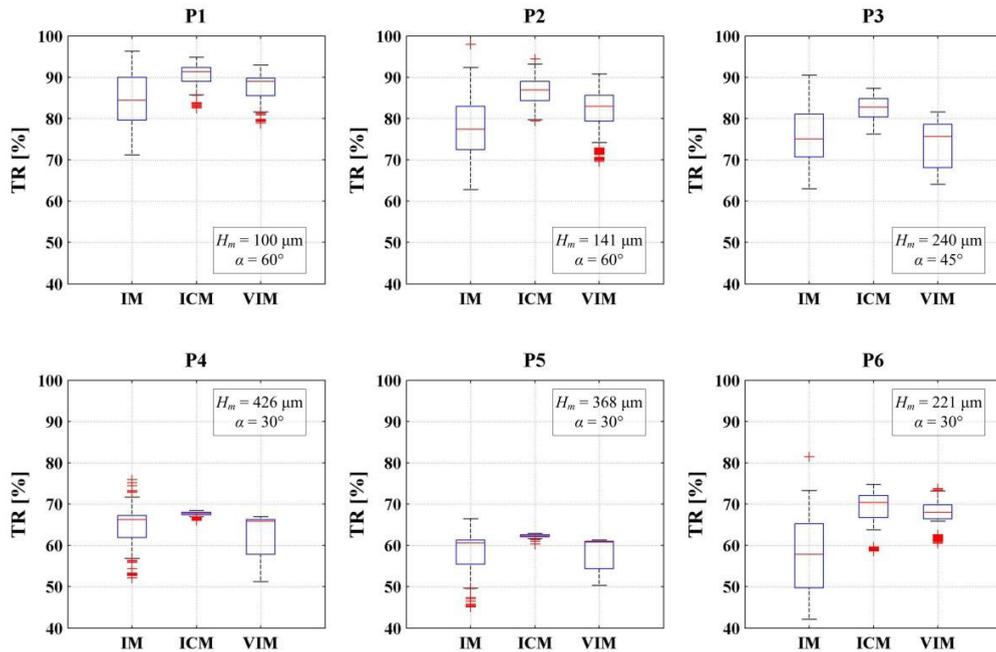


Fig.7.Box plots, whiskers plots and outliers of TR for the investigated injection moulding methodologies and for all considered prism geometries

It can be observed that there is a significant statistical difference between the transcription ratio of the three methodologies. Specifically, the ICM process obtained the highest average transcription ratio and the lowest

dispersion. Accordingly, ICM can be recognized as the most precise and repeatable of the three injection molding methodologies.

The average transcription ratio of the VIM methodology is lower than ICM but higher than IM for all prism geometries. The dimension of the box of the boxplot of VIM is in several cases of the same size of IM, in other cases slightly smaller. This analysis evidences that VIM is a minor improvement of the conventional injection molding process, and its effectiveness depends on the application.

In cases P4, P5, P6, where the prism angle α was 30° and 45° , the transcription ratios were smaller than other prism geometries. For example, cases P3 and P6 had the same prism height $H_m = 250 \mu\text{m}$ and two different prism angles, 45° for P3 and 30° for P6. Transcription ratio for P3 was about 75-80% whereas for P6 it was 60-70%. Therefore, the transcription ratio was low when the prism angle α was small, which could be reasonably expected. Similarly, geometries P4, P5 and P6 had the same prism angle $\alpha = 30^\circ$ and decreasing prism height H_m . It can be seen that the transcription ratio in these cases was in the range 60-70%. According to this observation, the prism height H_m did not have a significant effect on the transcription ratio.

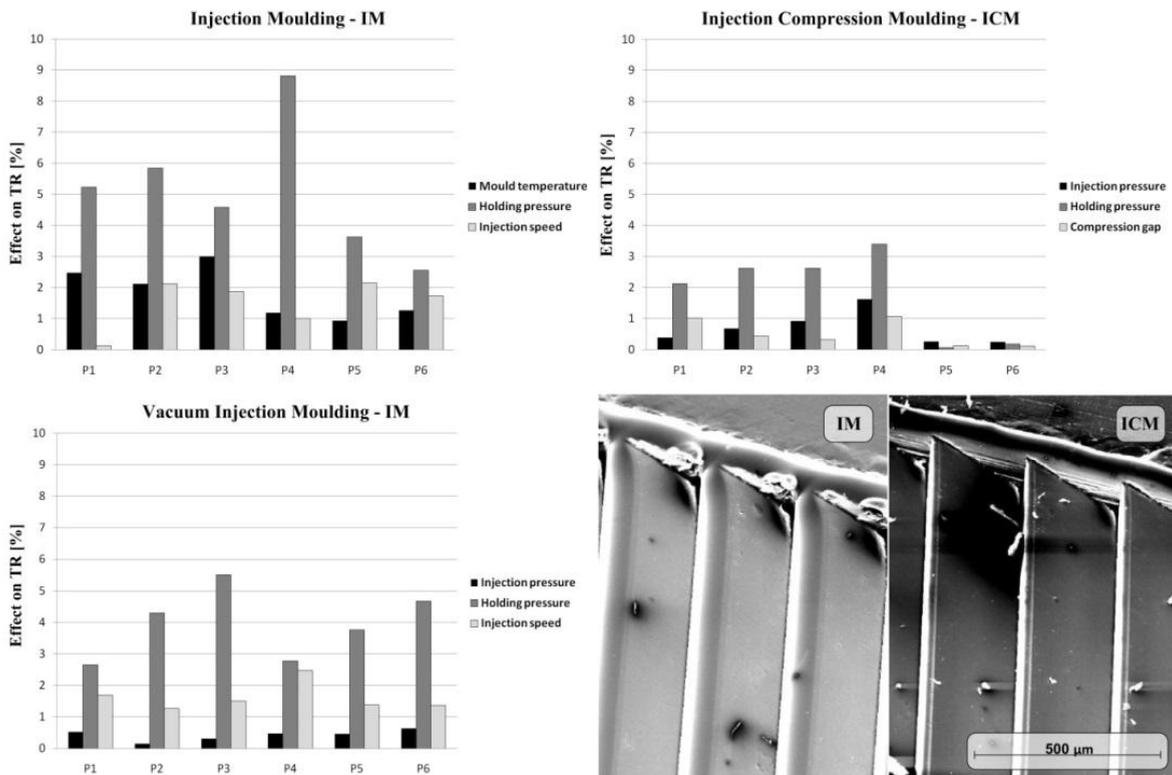


Fig.8. Average effects of the factors and SEM inspection of prisms obtained with IM and ICM

The average effect of the factors for each injection molding methodology and for each prism geometry together with an example of the molded prism geometries obtained with IM and with ICM are shown in Figure 8.

The most relevant factor for all the injection molding processes was the holding pressure, which caused a variation of TR between 2% and 9% for IM, 0% and 3.5 % for ICM, 2.5% and 5.5% for VIM.

For IM, the second most relevant factor was the mould temperature for larger prism angles – geometries P1, P2 and P3 – and injection speed for smaller prism angles – geometries P4, P5 and P6. These data were in accordance with previous studies. In the case of ICM, the second most relevant factor was the injection pressure which produced

a variation of TR around 1%. Injection speed was by far the second most relevant factor in the VIM process, producing a variation of TR around 1-2%.

4. Conclusion

The application of innovative injection molding methodologies – Injection Compression Molding (ICM) and Vacuum Injection Molding (VIM) – for the mass replication of optical microscale plastic components was compared to conventional injection molding. Injection compression moulding process can be performed only on dedicated machines, whereas vacuum injection moulding process can be applied to conventional injection moulding machine with minor set-up and mould modifications. Vacuum injection molding implies an increase in cycle time due to the time needed to reach the vacuum condition inside the cavity.

The analysis of the transcription ratio data derived from experiments evidenced that ICM is most precise and repeatable of the three injection molding methodologies, whereas VIM is a minor process improvement. However the maximum transcription ratio was strongly dependent on the optical prism geometry. Specifically, high levels of transcription ratio were reached only when the prism angle was large. There was no evidence of a strong effect of the height of the prism H_m on the transcription ratio.

Holding pressure was the main factor influencing all injection molding processes and producing variations of the TR up to 9% for IM, 3.5% for ICM and 5.5% for VIM. The transcription ratio obtained by IM was also influenced by the mould temperature and injection speed. Injection speed was also the second most relevant factor influencing the VIM process.

It would be of further interest to continue the research on this topic by combining the ICM and VIM methodologies and extending the investigation to other prism geometries.

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