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Comparison of micro and conventional injection moulding based on process precision and accuracy

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Abstract

Replication-based processes enable the large-scale production of precision and micro components made of many materials. As for polymers, injection moulding represents the most common technological solution. Micro polymer parts can be, in most cases, either manufactured by conventional injection moulding (IM) or by micro-injection moulding (μ IM). However, fundamental differences exist among the two processes. The present study aims at comparing IM and μ IM in terms of accuracy and precision of moulded parts. The same micro thermoplastic elastomer (TPE) component was manufactured using the two technologies on two different machines by means of multi-cavity moulds. The produced batches were assessed using a precision scale and a focus variation microscope. The cavities of the moulds were also measured in order to evaluate the pure replication capability by eliminating any influence caused by dimensional variations of master geometries. Measurement uncertainty was evaluated using ISO 15530-3. The data-based comparison revealed that μ IM was better suitable for meeting the high precision and accuracy demands typical of micro productions, allowing also to achieve a better cavity balance.

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1. Introduction

Conventional injection moulding is the most used manufacturing process for the production of parts made of polymeric materials. It is a discontinuous and cyclic replication technology that enables the fast and extremely repeatable manufacturing of net-shaped parts. The process can be fully automatized to achieve the extremely high throughput rates required for setting large-volume productions.

In recent decades, miniaturization of components has become one of the principal technological drivers in numerous engineering sectors [1]. The rapidly growing demand of micro-scaled components enabled the development of new manufacturing processes aiming at meeting the new accuracy and precision requirements. In many cases, well established technologies were adapted to micro-manufacturing by increasing their performances and decreasing their scale of action. In particular, conventional injection moulding (IM) was downscaled into micro-injection moulding (μ IM) [2]. Although IM and μ IM share the same overall process cycle, they also have fundamental differences and new challenges arise when the process has to be adapted to the micro-scale. In order to accomplish this, specific micro tooling processes, new measuring techniques

and new design approaches must be adopted [3]. The injection moulding machine has to be also modified: conventional ones are designed with a reciprocating screw, while dedicated μ IM ones typically have a screw for plasticising pellets and a separate plunger (diameter of 5 mm down to 2 mm) for metering and injection [4]. This alternative solution enhances the accuracy of polymer melt dosing, since injection plungers are much lighter and thus more precisely controllable than conventional reciprocating screws. Dedicated μ IM machines are also capable of providing higher injection speeds that are usually required to oppose the premature solidification of micro parts due to the larger surface-to-volume ratio. Finally, fully electric drives and new demoulding concepts are both used to improve process repeatability. These characteristics make μ IM the preferential method for the manufacture of polymer micro parts [5], which are defined as belonging to one of these classes [6]:

- Part whose mass is in the order of milligrams.
- Part with overall dimensions typical of standard plastic products but featuring micro-structured regions.
- Parts with dimensional tolerances in the micrometre range.

In many cases, such parts can be manufactured by both IM and

μ IM. IM is typically used to mould micro parts when small production batches are needed and the investment cost related to the purchase of a dedicated μ IM machine is not justified. When adopting this solution, large sprues are needed to achieve the minimum necessary shot weight for a conventional machine. This can lead to feed systems that account for 90 % of the injected plastic volume [4].

Although the differences between IM and μ IM in terms of process capabilities are well known, few studies report an actual comparison based on quantitative dimensional data. Giboz et al. [7] investigated morphological differences between high-density polyethylene (HDPE) macro and micro moulded parts. They observed that the size of crystalline entities, and consequently the product performances, was strongly influenced by the dimensional scale of the moulded component. Liu et al. [8] focused on morphology of isotactic polypropylene (iPP) moulded in macro and micro rectangular parts, discovering that μ IM provided a higher degree of crystallinity than IM. Sortino et al. [9] evaluated different moulding technologies when replicating optical micro structures in poly(methyl methacrylate) (PMMA). They showed that the addition of a compression phase proved essential in enhancing the replication performance of the moulding process. All the experiments were performed using the same conventional injection moulding machine.

No studies whose focus is the direct comparison between IM and μ IM in terms of replication precision and accuracy were found. This paper presents a comprehensive investigation of the two technologies based on process replication capabilities. The same micro plastic component was moulded using both an IM and a μ IM machine and the produced parts measured using a precision scale and a state-of-the-art focus variation microscope.

2. Materials and methods

2.1. Case study

The investigated micro part was a thermoplastic elastomer (TPE) component used in medical applications. TPE was selected since it provided the desired softness combined with a level of mouldability that enabled an effective and repeatable miniaturized replication process [10]. Fig. 1 shows the geometry of the micro part, which is cylindrical and has a through hole generated by a pin coaxial to the cavity. Two diameters are indicated: outer top diameter (ODt) and inner bottom diameter (IDb). These diameters are crucial to part functionality and are the geometrical outputs which this study focused on. The selected component well represents the class of cylindrical micro plastic part having a through hole. Moreover, by measuring an outer and an inner diameter, geometries generated by replication of cavities and pins were both investigated. The distinction between these two types of features is important: if, on one hand, the polymer is free to shrink in correspondence with outer diameters, on the other, the presence of the pin impedes the material to freely shrink for inner diameters, thus creating a constrained shrinkage phenomenon and influencing the final shape of the component. Being the dimensional tolerance specified as $\pm 50 \mu\text{m}$ for both ODt and IDb and the nominal part mass equal to 20 mg, the component is indeed a micro plastic

Table 1. Process parameters used for IM and μ IM.

Process parameter	IM	μ IM
Injection speed/(mm/s)	40	160
Holding pressure/bar	350	350
Melt temperature/ $^{\circ}\text{C}$	220	220
Mould temperature/ $^{\circ}\text{C}$	40	40
Cycle time/s	17	8

part according to the aforementioned definitions.

The polymer used for both IM and μ IM experiments was a Thermolast[®] grade from Kraiburg TPE GmbH (Waldkraiburg, Germany).

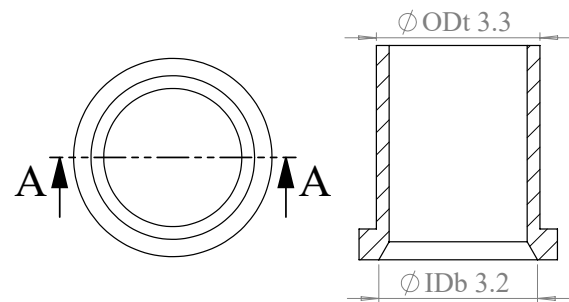


Fig. 1. Measured geometries of the micro component and their nominal dimensions in mm.

2.2. Conventional injection moulding set-up

Conventional injection moulding experiments were performed using an Arburg Allrounder 270 U machine having a 18 mm diameter reciprocating screw and a maximum clamping force of 400 kN. A two-plate mould with four cavities was used as master for replication (see Fig. 2). The volume of the feed system was equal to 980 mm³, accounting for the 92 % of the total amount of injected polymer. The usage of pin gates allowed to achieve automatic detachment of the parts from the feed system. The optimized process parameters for IM are indicated in Table 1.

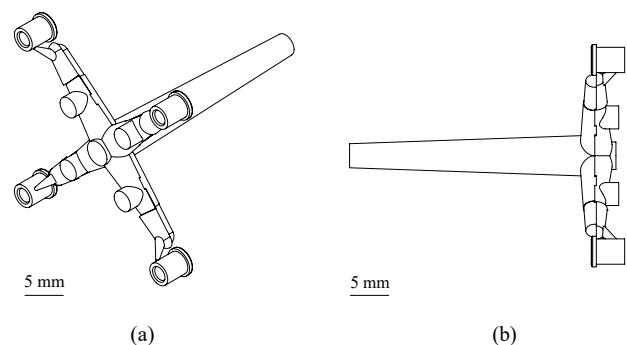


Fig. 2. (a) 3D view of the feed system used with the IM machine. (b) Lateral view of the feed system. Injection direction is left to right.

2.3. Micro-injection moulding set-up

Micro-injection moulding experiments were carried out with a state-of-the-art Wittmann-Battenfeld MicroPower 15 μ IM machine. Such machine has a 14 mm plasticisation screw and a

5 mm injection plunger. The maximum clamping force is equal to 150 kN. A different two-plate mould with four cavities was used in this case (see Fig. 3). The feed system was designed with a pin gate and had a volume of 174 mm³ that accounted for 66 % of the total injected amount of TPE. By comparing this value with the one of the previous case, it is clear that μ IM allowed to consistently reduce the amount of material waste (see Fig. 4), representing a valuable improvement with respect to production cost reduction. This also allowed to set the machine on a shorter cycle time and thus to increase the throughput (see Table 1). As for the other process parameters, the only difference among the two set-ups involved the injection speed. In fact, a higher value was used with the μ IM machine in order to balance for the smaller injection section.

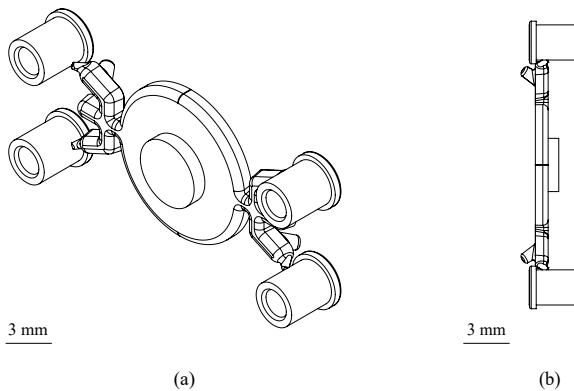


Fig. 3. (a) 3D view of the feed system used with the μ IM machine. (b) Lateral view of the feed system. Injection direction is right to left.

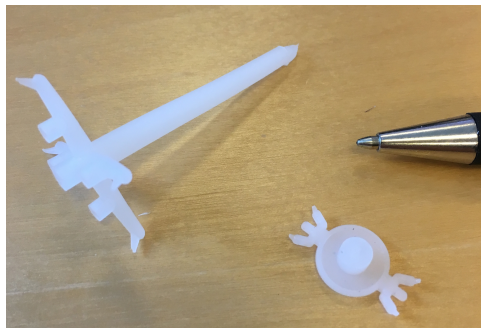


Fig. 4. Comparison of feed systems used for IM (left) and μ IM (right).

2.4. Measurements and uncertainty evaluation

A precision scale having 0.1 mg resolution (AW220, Shimadzu Corp., Kyoto, Japan) was used to carry out a preliminary investigation on process repeatability based on mass measurement. After discarding the first fifty shots, ten consecutively injected parts were collected per each one of the four mould cavities and then weighed for both IM and μ IM batches. The 80 moulded micro components were also dimensionally assessed using a 3D focus variation microscope (Alicona InfiniteFocus, Alicona Imaging GmbH, Raaba, Austria) with a 5 \times magnification objective (0.41 μ m vertical resolution and 1.75 μ m lateral digital resolution). In particular, top and bottom sides of each part were acquired and then levelled by applying a 1st order correction. This operation consisted of a planar correction, i.e. subtracting the planar deviation, identified as the least square

plane fitted to the original point cloud, from the raw acquisition. After that, the two measurands were extracted by fitting the points corresponding to the circles of interest (see Fig. 5) using the software MountainsMap[®] (Digital Surf, Besançon, France). Each acquisition was repeated three times in order to provide statistical robustness to the output and evaluate measurement repeatability.

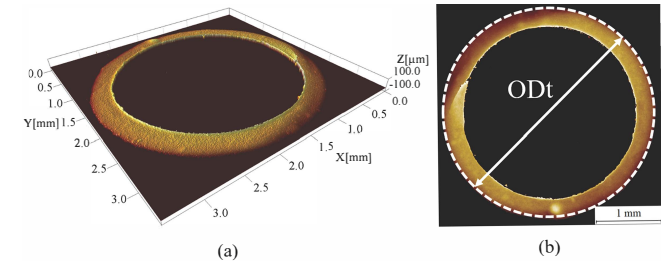


Fig. 5. (a) 3D acquisition of top side of a micro moulded part. (b) Interpolated circle and ODt measurement.

Cavities of both IM and μ IM moulds were measured with an optical microscope featuring 2.6 μ m lateral resolution (Infinity X-32, DeltaPix, Smørum, Denmark). ODt was measured on the mould cavities, while IDb on the pins. By doing this, the mould geometries were calibrated and a reference for the replication was obtained. The effect of any difference among the four master dimensions was thus eliminated from the process analysis. An uncertainty evaluation was performed to evaluate the quality of dimensional measurements carried out on the moulded parts. ISO 15530-3 [11] was used for calculating the expanded uncertainty U of ODt and IDb measurements. This uncertainty evaluation technique is based on the substitution method, which allows to estimate the error of the measuring instrument by repeated measurements on a calibrated artefact that is similar to the actual measurand. For this specific task, a 1 mm calibrated circle was used. In total, five uncertainty contributions were taken into account: u_{cal} , as declared on the calibration certificate of the artefact; u_p , uncertainty of the measurement procedure calculated as standard deviation of ten repeated diameter measurements of the calibrated circle; u_w , introduced by material and manufacturing variations of the moulded parts; u_b , related to the systematic error of the measurement process; and u_{res} , calculated considering the microscope digital resolution. u_w was calculated as:

$$u_w = \frac{\max(\vec{D}) - \min(\vec{D})}{2\sqrt{3}} \quad (1)$$

where \vec{D} is the vector collecting measurement values related to the three repeated acquisitions for one of the two measurands. The expanded uncertainty U was obtained by combining the aforementioned contributions according to the law of propagation of uncertainty:

$$U = k \times \sqrt{u_{cal}^2 + u_p^2 + u_w^2 + u_b^2 + u_{res}^2} \quad (2)$$

where a coverage factor k equal to 2 was selected in order to apply a 95 % confidence level. Table 2 and 3 show the uncertainty budgets for IM and μ IM parts respectively.

Table 2. Uncertainty contributions for IM parts. Results are averaged for the four cavities.

Uncertainty contributions	IDb	ODt
$u_{cal}/\mu\text{m}$	0.50	0.50
$u_p/\mu\text{m}$	0.09	0.09
$u_w/\mu\text{m}$	0.54	0.36
$u_b/\mu\text{m}$	$5 \cdot 10^{-5}$	$5 \cdot 10^{-5}$
$u_{res}/\mu\text{m}$	0.51	0.51
$U/\mu\text{m} (k = 2)$	1.8	1.6

Table 3. Uncertainty contributions for μIM parts. Results are averaged for the four cavities.

Uncertainty contributions	IDb	ODt
$u_{cal}/\mu\text{m}$	0.50	0.50
$u_p/\mu\text{m}$	0.09	0.09
$u_w/\mu\text{m}$	0.38	0.85
$u_b/\mu\text{m}$	$5 \cdot 10^{-5}$	$5 \cdot 10^{-5}$
$u_{res}/\mu\text{m}$	0.51	0.51
$U/\mu\text{m} (k = 2)$	1.6	2.2

3. Results

The uncertainty budgets provided a first notable result regarding the quality of the measurements. For IM parts, U was $1.8 \mu\text{m}$ and $1.6 \mu\text{m}$ for IDb and ODt respectively, and thus an uncertainty-tolerance ratio U/T of circa 4 % was achieved. The same was observed for the parts manufactured by μIM . Such a low U/T value confirmed that the measurement method was suitable for the task.

In this study, the replication fidelity was evaluated with the term Δ_D , which was defined as:

$$\Delta_D = \frac{D_{\text{polymer}} - D_{\text{mould}}}{D_{\text{mould}}} \quad (3)$$

where D_{polymer} is a generic diameter measured on the parts and D_{mould} is the correspondent geometry measured on the mould. This variable is normalized with respect to the mould dimensions and therefore allowed to get rid of the influence of any deviation between different cavities when comparing the two processes.

In the next paragraph, a first investigation based on mass measurements is presented. In the following ones, the replication capabilities of IM and μIM are discussed based on IDb and ODt measurements.

3.1. Mass measurements

Fig. 6 reports the mass measurement results. Considering process repeatability, both the moulding technologies provided comparable results, since standard deviations close to 1 % of the average value were observed in all cases. The cavity balance was better for the parts moulded with μIM , being results of cavity 1, 2, 3 and 4 on the same level. Parts moulded with IM, on the other hand, showed a larger dispersion with respect to cavity number, being the mass of cavity 1 not congruent with that of cavity 2 and 3. This finding could be directly correlated to the smaller injected volume and thus more homogeneous polymer melt provided by the μIM machine. However, being the exact volume of the four cavities unknown, this unbalance could have been also caused by different cavity volumes.

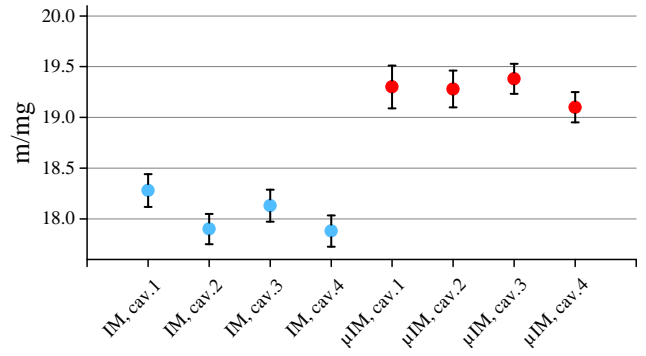


Fig. 6. Mass measurements results for IM (light blue) and μIM (red). The interval bars indicate the standard deviations of the ten measured parts.

3.2. IDb measurements

Fig. 7 shows the results related to IDb measurements. In general, μIM allowed to achieve a better replication than IM. In fact, Δ_{IDb} was always closer to zero and therefore the produced parts were more similar to mould dimensions when using the micro-scaled process. This was due to the fact that the filling phase was more efficient in μIM as a result of the faster injection and that the holding phase was more effective due to faster switch-over and smaller injection volume. Concerning cavity balance, both the technologies resulted in an effective multi-cavity replication process: the interval bars overlap for the four cavities of IM and μIM . The achieved repeatability was also almost constant among the four cavities.

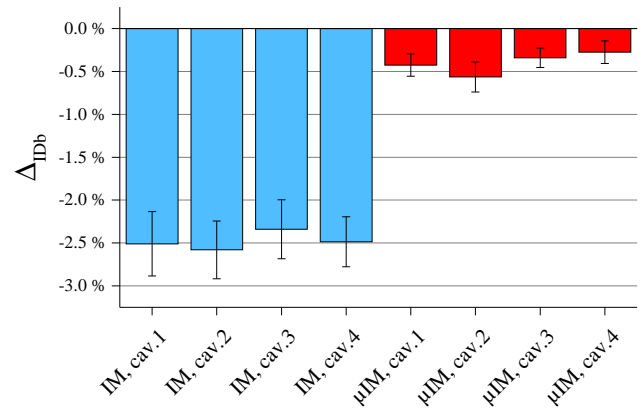


Fig. 7. Δ_{IDb} results for IM (light blue) and μIM (red). The interval bars indicate the 95 % confidence intervals for the mean.

When accuracy and precision of any process are considered, capability indexes turn particularly useful, since they are simple statistics that reveal if the desired specifications are consistently met [12]. In this investigation, since both repeatability and accuracy of the two processes were considered, the parameters C_p and C_{pk} were calculated for both IM and μIM and then compared. The two are defined as:

$$C_p = \frac{USL - LSL}{6\sigma} \quad (4)$$

$$C_{pk} = \min\left(\frac{USL - \mu}{3\sigma}, \frac{\mu - LSL}{3\sigma}\right) \quad (5)$$

where USL and LSL are the upper and lower specification limits respectively, μ is the data average and σ is the standard deviation. Such indexes allow to evaluate both precision and accuracy of the results with respect to the imposed design target and

tolerances. In particular, C_p is an indicator of the pure repeatability of the process with respect to the specification interval. The higher it is, the more repeatable is the process. On the other hand, C_{pk} provides also information on the capability of the process to meet the design target. Being the target set as the perfect replication of the master geometries in this study, C_{pk} was a direct indicator of the replication fidelity. Therefore, by taking into account these two variables, IM and μ IM were compared in terms of both precision and accuracy. Typically, C_p and C_{pk} values larger than 1.33, which represents a process able to operate on a four sigma level [12], are defined as satisfactory for manufacturing standards.

USL and LSL were set for Δ_{IDb} by considering 0 % of linear shrinkage as target, i.e. the case of perfect replication of the mould geometries. In fact, one of the objectives of the study was to determine which of the two processes allowed to achieve a better replication. By applying the interval identified by the 50 μ m tolerance, USL and LSL were equal to -1.56 % and 1.56 % respectively. Fig. 8 shows the distribution of measured Δ_{IDb} with respect to specification limits. Firstly, it is possible to observe that μ IM allowed to achieve a more precise production batch, being the data less disperse than for IM. All the parts moulded with μ IM provided Δ_{IDb} values falling inside the specification range, proving that the process was indeed able to meet the requirements. On the other hand, the IM batch was made of parts that all fell outside the lower specification limit, proving to be worse than the other technological solution also in terms of process accuracy. In particular, the replication level was not enough, in this case, for meeting the requirements of the micro production. The comparison of C_p and C_{pk} (see Table 4 and Table 5) confirmed the observations. Both the processes allowed to achieve a C_p value larger than 1.33, demonstrating an acceptable precision performance. However, μ IM, being characterized by a C_p of 5.06, proved to be much more repeatable than IM, which provided a value of 2.11. As for the accuracy with respect to the target of perfect replication, the comparison of C_{pk} clearly showed that μ IM performed better than IM, demonstrating that the adoption of micro technology resulted in an enhanced replication of the mould geometries.

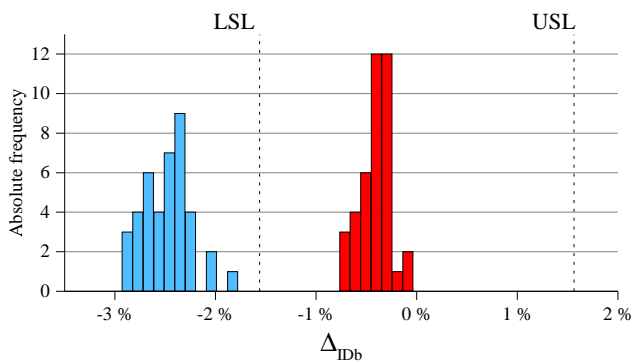


Fig. 8. Δ_{IDb} absolute frequency distribution for IM (light blue) and μ IM (red). LSL and USL are indicated by the vertical dashed lines.

3.3. ODt measurements

Fig. 9 reports the results of ODb measurements. As for IDb, μ IM generally resulted in a better replication. However, this conclusion is not as straightforward as with the other measurement: for both processes, a certain discrepancy between the dif-

Table 4. C_p values of IM and μ IM processes for the two dimensional measurands.

C_p	IM	μ IM
Δ_{IDb}	2.11	5.06
Δ_{ODt}	1.85	2.11

Table 5. C_{pk} values of IM and μ IM processes for the two dimensional measurands.

C_{pk}	IM	μ IM
Δ_{IDb}	-1.24	3.76
Δ_{ODt}	0.57	1.29

ferent cavities was present. In particular, cavities 1 and 3 of IM were replicated with a level comparable to the μ IM production, while cavity 2 and 4 resulted in a lower replication performance, proving the presence of cavity unbalance. μ IM also provided results that varied with the cavity number, even though less than the other process.

When comparing the replication level of the two measurement outputs, it is possible to note that the benefit introduced by using a micro-injection moulding machine was more pronounced for IDb. In fact, for ODb, there was not the substantial improvement in terms of replication observed for IDb when using μ IM instead of IM. Therefore, it can be concluded that the usage of a μ IM machine was more beneficial for IDb than for ODb. Such a difference might be caused by the fact that IDb was obtained by replicating an internal geometry (i.e. the pin), while ODb by replicating an outer geometry (i.e. the external cavity). Therefore, the polymer was free to shrink on ODb, but it was not for IDb, since the presence of the pin did not allow a free deformation of the injected polymer part. Such a constrained shrinkage typically generates a concentration of residual stresses on internal geometries (e.g. holes) that enhances the shrinkage of the moulded part once it is ejected from the mould [10]. Being the shrinkage amount of IDb substantially decreased when applying μ IM, it may be possible that the use of μ IM instead of IM allowed to reduce the residual stresses and the consequent shrinkage.

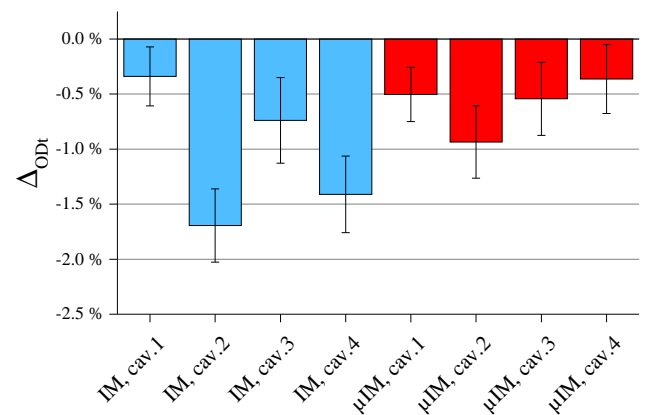


Fig. 9. Δ_{ODt} results for IM (light blue) and μ IM (red). The interval bars indicate the 95 % confidence intervals for the mean.

The process capability indexes C_p and C_{pk} were used to compare the two processes with respect to ODb also. As in the previous case, 0 % of shrinkage was taken as target and LSL and

USL were consequently set to -1.51 % and 1.51 % respectively in order to represent the desired specification range. Fig. 10 shows the experimental distributions of Δ_{ODt} when moulded with μ IM and IM. In this case, 40 % of the part moulded with IM fell outside the specification range, confirming that a better replication was achieved with respect to the other measurand. However, μ IM once again led to a better replication of the master geometry, being all Δ_{ODt} of the parts moulded with this process inside the range identified by LSL and USL. μ IM was also more precise than IM, being its distribution of results narrower. These findings were mirrored by C_p and C_{pk} . In fact, μ IM provided a slightly higher C_p value (see Table 4), showing that a higher process repeatability was achieved with respect to this geometrical output. The micro-scaled technology also resulted in a higher replication performance, as shown by the larger C_{pk} (see Table 5). However, in this case, being C_p and C_{pk} of the two produced batches closer than for IDb, the choice of adopting μ IM led to a smaller improvement.

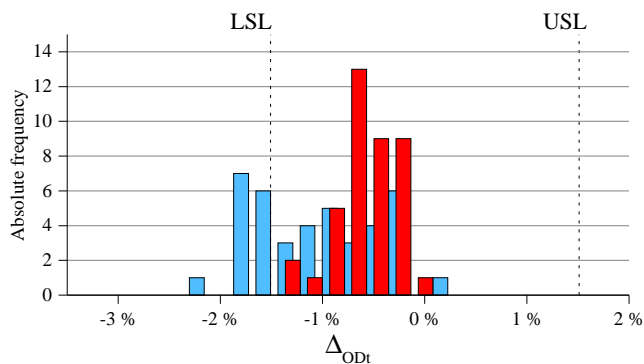


Fig. 10. Δ_{ODt} absolute frequency distribution for IM (light blue) and μ IM (red). LSL and USL are indicated by the vertical dashed lines.

4. Conclusions

The research reported in the present paper compared IM and μ IM by analysing precision and accuracy, intended as the capability of meeting a perfect replication target, of the moulding process when replicating the same geometry moulded with a conventional and a micro-injection moulding machine. Two different four-cavity moulds were employed in the investigation: a conventionally-sized mould equipped with four micro cavities and a micro tool engineered specifically for a micro moulding machine, also equipped with four micro cavities having the same geometry as in the other mould. All cavities in both moulds were calibrated with respect to the selected measurands using a metrological approach. To the best knowledge of the authors, this comparison is the first of its kind published in literature.

The following conclusions are drawn from the study:

- The choice of adopting μ IM instead of IM resulted in a consistent reduction of material waste due to a smaller feed system (155 mg against 873 mg). For such reason, and for a considerable shortening of the cycle time, using μ IM instead of IM represented a valuable choice for the sake of production cost minimization.
- As revealed by results of mass measurements, a better cavity balance was achieved when using μ IM. This improve-

ment was probably linked to the more precise dosing of μ IM and to the smaller amount of injected polymer.

- For the inner diameter IDb, μ IM provided a relevant improvement in terms of master replication and more accurate and precise results, as indicated by much higher C_p and C_{pk} values.
- For the outer diameter ODt, μ IM provided an improvement in terms of precision and accuracy of the moulded parts.
- The choice of using μ IM rather than IM proved to be beneficial with respect to both inner and outer diameter. However, a bigger improvement was observed for IDb. This could be caused by the fact that adopting μ IM helped reducing the residual stresses generated as a consequence of the constrained shrinkage of the inner part of the moulded component.

Future work will be dedicated to a more comprehensive metrological analysis of the parts moulded with IM and μ IM and to the quantification of the residual stresses induced by the two processes.

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