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Investigation on the micro injection molding process of an overmolded multi-material micro component

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Abstract

Micro injection molding (µIM) is one of the few technologies capable of meeting the increasing demand of complex shaped micro plastic parts. This process, combined with the overmolding technique, allows a fast and cost-efficient production of multi-material micro components, saving numerous and difficult assembly steps, being the plastic molded directly on a metal substrate. In this scenario, an investigation on the fully automated micro overmolding manufacturing technology of a three-material micro component for acoustic applications was carried out. Preliminary experiments allowed identifying an initial process window by considering the main defects affecting the part quality. Within this range, the effect of three injection molding parameters, namely mold temperature, melt temperature and injection speed, was evaluated with respect to the critical geometrical characteristics of the component. An optical CMM with sub-micrometric resolution was employed for the measurements. Results show that the process parameters have a significant influence on some component features, while others do not show a dependence on the process. Finally, the assembly accuracy was statistically verified considering the part alignment as indicator.

Keywords: Micro Injection Molding, Micro overmolding, Optical micro metrology

1. Introduction

Over the last decade, the need of miniaturized multi-functional components increased consistently in many engineering fields as electronics, medicine, biotechnology, communications, avionics, etc. [1, 2]. In order to meet this growing request, the international manufacturing community reacted either by developing brand new processes or by adapting already existing ones to the new challenging precision and accuracy demands. Micro injection molding (µIM) is the miniaturized counterpart of the conventional injection molding technology [3]. This process combines the evident advantages of its macro counterpart (e.g. the cost efficient production of complex and net-shaped plastic parts) with the capability of accurately manufacturing micro components having either overall dimensions in the micrometer range or outer dimensions in the millimeter range, but exhibiting micrometric features. Even though the physics behind the two processes is the same, many challenges arise when downscaling conventional injection molding: more accurate machines as well as new measuring solutions are needed in order to guarantee the demanded quality for the production. Moreover, considering the requested high precision, the process window becomes tighter and thus more difficult to control [4] since a very small difference in the settings can cause a relevant deviation on the output.

A further issue generated by the micrometric dimensions of the micro components is related to the assembly. In fact, manual assembly operations are still prevailing nowadays, since the lack of flexibility of automatic assembly procedures makes the latter affordable only when high throughput are required [5].

In this regard, the overmolding technique can be successfully combined with micro injection molding in order to save costly and laborious assembly steps. Overmolding refers to the process that molds plastic “over” a substrate made of another material, allowing the direct manufacture of a multi-material component. The insert is typically made of plastic or metal. One of the main uses of this technique applies to thermoplastic elastomers (TPE), whose softness and damping properties are used in combination with rigid substrates in order to add functions such as grippability, vibration insulation and enhanced ergonomics [6]. Recently, the overmolding technique found an innovative application in the electronic field, where it is currently used in the production of MEMS due to the wide range of materials it can successfully combine. In this respect, Schreier-Alt et al. [7] investigated the polymer flow of epoxy polymer during overmolding applied to printed circuit boards encapsulated as a Mold Array Package (MAP). However, the present literature still lacks a study focused on the effect of the process parameters on the geometrical quality of an overmolded micro part.

The present paper reports about an investigation on the process parameters effect in the production of TPE micro overmolded suspension rings utilized as part of the tip of a high performance phono cartridge. The experimental setup, along with the measurement strategy, is presented in Section 2. Section 3 deals with the results while a final discussion follows in Section 4.

2. Materials and methods

The micro part object of this study is a micro assembly made of three components: an aluminum cantilever, a magnet rod and a TPE micro-ring. Fig. 1

shows the component appearance as well as its critical nominal dimensions. The aluminum cantilever and the magnet rod are press-fitted together before the molding operation, and thus they constitute the metal substrate over which the TPE micro ring is molded in the following phase. The overmolding solution allows a relevant decrease of the manufacturing time since the mounting of the micro ring on the metal assembly is eliminated from the production chain.

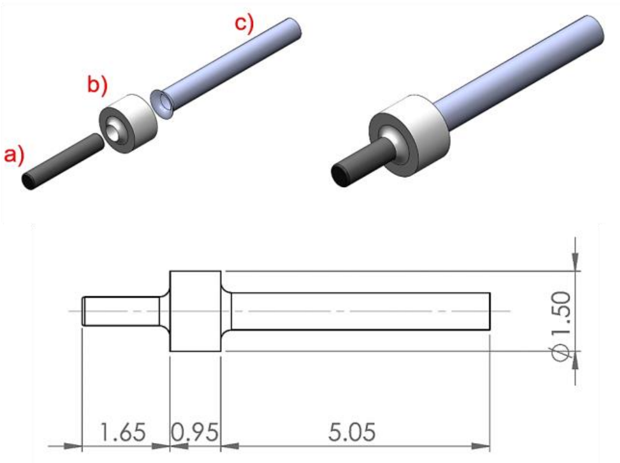

Fig. 1. Micro assembly three dimensional model and main dimensions in mm. (a): Magnet rod. (b): TPE micro-ring. (c): Aluminum cantilever.

2.1. Experimental setup

The micro injection molding experiments were carried out using a Wittmann-Battenfeld MicroPower 15 machine. The injection unit presents a Ø 14 mm screw for plasticization and metering, and a separate injection plunger of Ø 5 mm. The mold is made of three plates and has two cavities. The metal insert (i.e. the aluminum cantilever and the magnet pressed together) is picked up from a specifically designed magazine tool by using the robot arm coupled with the machine and then inserted inside the mold. After molding, the part is demolded and replaced in the free spot left inside the magazine tool using the same robot arm. A fully automated manufacturing process is therefore ensured.

Preliminary experiments allowed identifying an initial process window by taking into account the most visible defects affecting the part quality. In particular, extensive flashes and gate mark were present at high values of holding pressure. Flash is a defect manifested by the presence of excessive material at locations where the mold is separated and it is usually caused by high pressures and temperatures. In this case, the phenomenon is also helped by the lower viscosity of thermoplastic elastomers compared to the one of thermoplastics. As regards the gate mark, it is an evident irregularity caused by the incorrect separation of the gate from the part. These two defects were always observed in parts molded with holding pressure higher than 150 bar, regardless of the other injection molding parameters. In order to find a level of this parameter that could guarantee a complete filling without degenerating in flashes and gate marks, the standard short shot analysis [8] was applied. By doing so, the optimal level of the holding pressure was found at 80 bar. Fig. 2 shows two examples of a defected and a defect-free part.

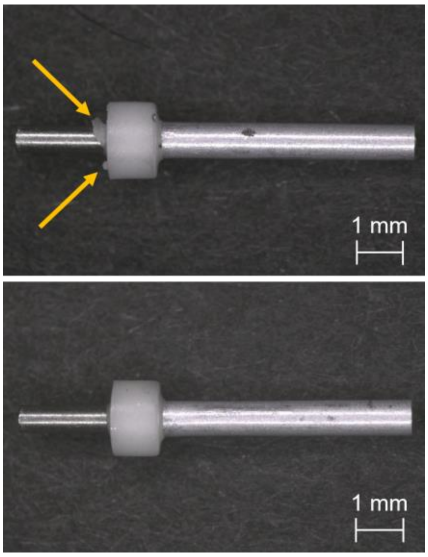

Fig. 2. Micro-part molded with holding pressure equal to 200 bar (up) and 80 bar (down). The flash is indicated by the upper arrow, while the gate mark by the lower one.

The holding pressure was mantained at his value throughout the all investigation.
In order to analyze the effect of the other process parameters on the part quality, the mold temperature, the melt temperature and the injection speed were varied on three levels each (see Table 1).

Table 1: Experimental process parameters.

Process parameters	Values
Melt temperature T_{melt} [°C]	200, 210, 220
Mold temperature T_{mold} [°C]	30, 40, 50
Injection speed v_{inj} [mm/s]	80, 90, 100

Being the experimental campaign still in an optimization phase, the three experimental factors were changed one at time while keeping the central point. Five parts for each cavity have been stored after discarding the first ten, resulting in a total number of 70 available molded samples.

2.2. Measuring methodology

In order to assess the quality of the molded parts with respect to the selected process parameters, two geometrical characteristics were considered. The first one is the diameter *D* of the TPE micro-rings, being fundamental for the functionality. The second one is the alignment between the micro-ring axis and the metal substrate axis, described by the angle *α*. This latter feature is important since it is a synthetic indicator of the accuracy of the multi-material assembly required for a correct operation of the phono cartridge. If a misalignment was present, the overmolded component would not provide the desired dampening. The main reason that could cause a misalignment is the so-called core shift that occurs as a spatial deviation of the insert from the original position due to unbalanced cavity pressures. In the case under study, it might happen since the gate is not symmetrical with respect to the metal insert axis.

An optical CMM machine (DeMeet 220 from Schut Geometrical Metrology) with 0.5 µm lateral resolution was employed to characterize the micro insert moulded parts. In particular, being the measurements two-dimensional, the diameter and the alignment angle were measured in three different circumferential positions around the component axis in order to consider their variation. Thus, three measurement outputs were available for each analyzed part. Each measurement was repeated five times, showing a high repeatability, being the maximum observed standard deviation equal to 0.5 µm for *D* and 0.05 ° for α.

Fig. 3 shows the measurement scheme and a view of the optical CMM interface.

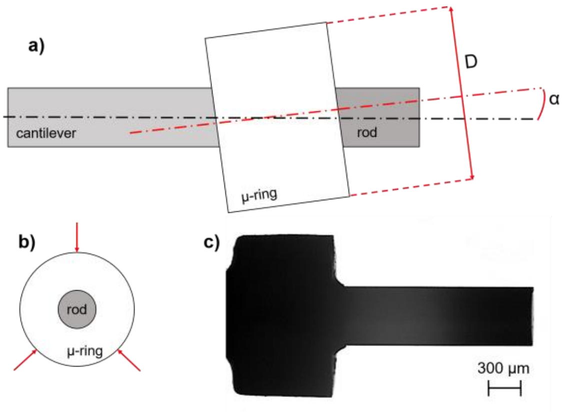

Fig. 3. (a): Measurement scheme. The diameter *D* and the angle *α* are indicated. (b) The three circumferential measuring positions. (c) Micro assembly as viewed by the optical CMM.

Along with the diameter *D* and the angle *α* (both considered as the average of the measurements in the three circumferential positions), the difference between the maximum and minimum values of *D* among the three measuring positions was considered. This quantity is calculated as:

$$\Delta = \mathrm{Max}(D_i) - \mathrm{Min}(D_i) \qquad i = 1, \ldots, 3 \qquad (1)$$

and it was defined in parallel to the roundness [9]: a large value of *Δ* corresponds to low roundness while a low value of *Δ* characterizes a micro ring with a high roundness.

It must be stated that the mold cavities were not measured because of production reasons. Thus being the real mold cavity diameters unknown, the measured *D* cannot directly be compared with the nominal Ø 1.50 mm shown in Fig. 1.

3. Results and discussion

The measurements of the three outputs were analyzed in order to investigate the process parameters effects. Firstly, it was statistically verified that the cavity has no effect on *D, α* and Δ by using the Analysis of Variance (ANOVA). Thus, the two cavities were not considered as experimental factor in the following analysis.

Fig. 4 and Fig. 5 depict the interval plots for the diameter *D* and the roundness parameter *Δ*.

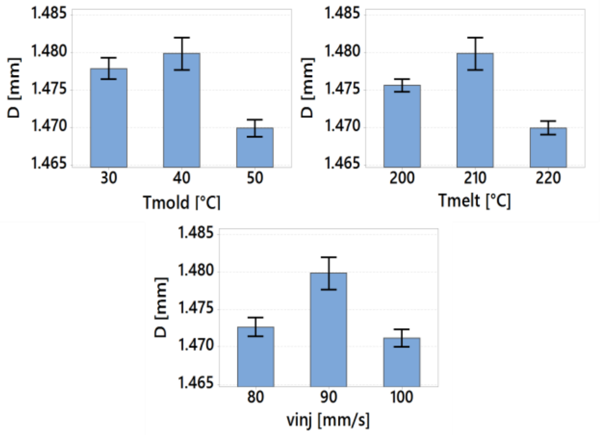

Fig. 4. Interval plots of *D*. The error bars are shown.

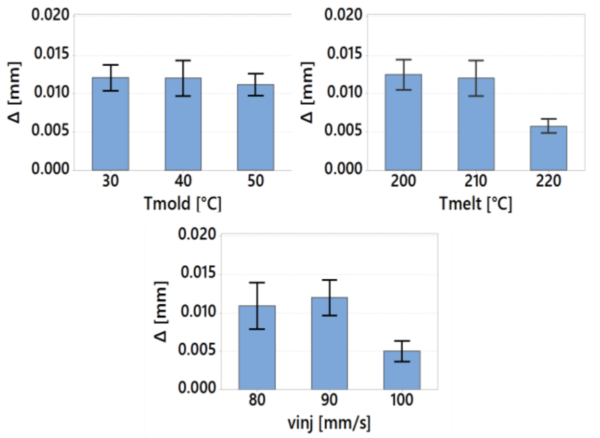

Fig. 5. Interval plots of *Δ*. The error bars are shown.

Concerning the ring diameter *D*, all the process parameters have a significant effect. In particular, the central values of T_{mold}, T_{melt} and v_{inj} provide the largest response equal to 1.480 mm. It is also worth to notice that the highest levels of the parameters result in the smallest *D*: this is unexpected since usually, in micro injection molding, very high mold temperature and injection speed are utilized in order to obtain a complete filling of the cavity [10] by preventing a premature freezing of the gate. In this particular case, however, the results show that the replication quality increases up to certain upper limit of T_{mold}, T_{melt} and v_{inj}, after which it drops. This observed behavior suggests that the viscosity of the TPE material undergoes a too drastic reduction when molding with the high levels parameters, resulting in a not optimal filling of the mold cavity. In fact, the viscosity reduction facilitates the formation of flashes, which can cause the material to fill the mold parting lines. Thus, a reduced amount of material remains inside the cavity, leading to a worse replication. This effect plays an important role in micro injection molding, since a very small amount of material is injected.

On the other hand, the roundness parameter *Δ* is not influenced by the mold temperature but only by T_{melt} and v_{inj}. The lowest *Δ* (equal to 0.005 mm) was measured when molding at high levels of these two parameters, meaning that a better dimensional stability of *D* among the three circumferential positions has been achieved. This finding reveals that high

levels of melt temperature and injection speed provide a better roundness but, at the same time, a worse result with respect to the target dimension of *D.*
Fig. 6 presents the interval plots related to the measurements of *α*.

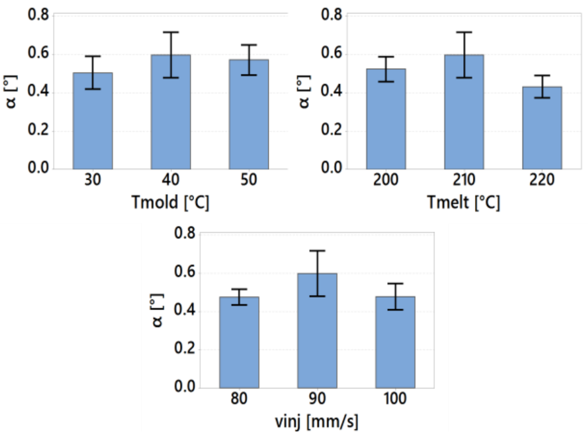

Fig. 6. Interval plots of *α*. The error bars are shown.

In this case, there is no effect of the three process parameters on the measured output, as also confirmed by the ANOVA. In fact, the average values and the standard deviations have the same order of magnitude of 10^{-1}°. This proves that the alignment of the micro assembly does not depend on any of the investigated injection parameters. It is also important to note that the average angle ranges between 0.4° and 0.6°.
In order to assess the alignment of the component, the whole population of measured angles was considered in a t-test on the mean with the aim of statistically comparing it with an imposed limit of 1°. For this purpose, all the 210 measured angles (3 per each one of the 70 molded specimens) were taken into account. The tested hypotheses were: "H_0: $\mu_\alpha \geq 1°$" and "H_0: $\mu_\alpha < 1°$", being μ_α the mean of the α population. The null hypothesis H_0 was then rejected at a 99% confidence level, proving that the limit of 1° on the angle is hardly overcome with such a process. Thus, the good alignment of the micro component was verified.

4. Conclusions

The micro injection molding process of a micro overmolded multi-material component was investigated in this work. The effect of three process parameters on three critical geometrical features was evaluated.
The diameter of the micro-ring *D* showed a significant dependence on all the process parameters. In particular, the central levels provided the largest output, meaning that a better cavity replication was achieved. The high levels, on the other hand, resulted in the smallest *D*. This event suggests that there is a limit upon which the viscosity of the TPE assumes too low values, preventing an optimal cavity filling.
The roundness parameter *Δ* was calculated for each molded part in order to address the dimensional stability of *D*. It was found that the best roundness is achieved with the high levels of T_{melt} and v_{inj}, while T_{mold} does not have a significant effect.
The angle *α* describes the alignment between the overmolded micro ring and the metal substrate. No effect of the process parameters was observed on this geometrical characteristic. Therefore, the component assembly accuracy does not depend on the investigated process parameters. The mean value of *α* has then been tested thought a t-test, proving that a tolerance of ± 1° would be consistently respected. Hence, the misalignment of the multi material micro assembly assumes on average an acceptable value.
Future studies will be dedicated to the investigation of the effect of other process parameters as for instance the holding pressure and the holding time. Numerical FE simulations will be also employed in order to predict the filling behavior and the warpage of the micro overmolded part.

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