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Published in:

Proceedings of the 2017 World Congress on Micro and Nano Manufacturing

Publication date:
2017

Document Version
Early version, also known as pre-print

[Link back to DTU Orbit](#)

Citation (APA):

Baruffi, F., Calaon, M., Tosello, G., & Elsborg, R. (2017). Investigation on the micro injection molding process of an overmolded multi-material micro component. In Proceedings of the 2017 World Congress on Micro and Nano Manufacturing

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

WCMNM
2017
No.

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Abstract

Micro injection molding (μ IM) 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 has been carried out. Preliminary experiments allowed to identify an initial process window by considering the main defects affecting the part quality (flashes and gate marks). Within this range, the effect of three injection molding parameters, namely mold temperature, melt temperature and injection speed, has been evaluated with respect to the critical geometrical characteristics of the component. An optical CMM with sub-micrometric resolution has been employed for the measurements. Results show that the process parameters have a significant influence on some component features, while others mainly depend on the insert alignment inside the micro mold cavity.

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

1. Introduction

Over the last decade, the need of miniaturized multi-functional components has 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 (μ IM) 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 injection molding: more accurate machines as well as new measuring solutions are needed in order to guarantee the requested quality for the production. Moreover, the process window becomes tighter and thus more difficult to control [4] since a very small difference in the settings can cause a relevant difference on the output given the requested high

precision.

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, overmolding found an innovative application in the electronic field, where it is currently used in the production of MEMS given the wide range of materials it can successfully combine together. 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 a overmolded micro part geometrical quality.

The present paper reports about an investigation

on the process parameters effect in the production of a thermoplastic elastomer micro overmolded suspension ring 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.

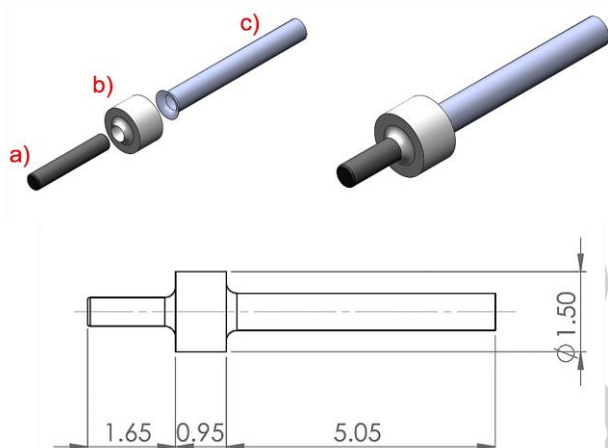


Fig. 1. Micro assembly three dimensional model and main dimensions in mm. (a): Magnet rod. (b): TPE micro-ring. (c): Aluminum cantilever.

2.1. Experimental setup

The micro injection molding experiments have been carried out using a Wittmann-Battenfeld MicroPower 15 machine. The injection unit presents a \varnothing 14 mm screw for plasticization and metering, and a separate injection plunger of \varnothing 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, ensuring a fully automated manufacturing process.

Preliminary experiments allowed to identify 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 100 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] has been 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.

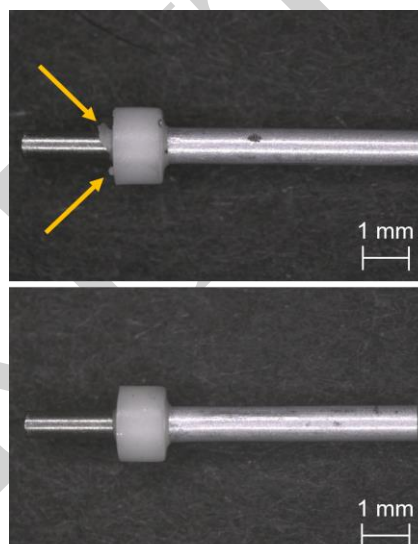


Fig. 2. Micro-part molded with holding pressure equal to 200 bar (up) and 80 bar (down). The flash is indicated by the upper arrow, while the gate mark by the lower one.

The holding pressure has then been kept 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 have been 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 have been 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 have been 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 $0.5\ \mu\text{m}$ lateral resolution has been employed to characterize the micro insert moulded parts. In particular, being the measurements two-dimensional, the diameter and the alignment angle have been 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 has been repeated five times, showing a high repeatability, being the maximum observed standard deviation equal to $0.5\ \mu\text{m}$ for D and 0.05° for α .

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

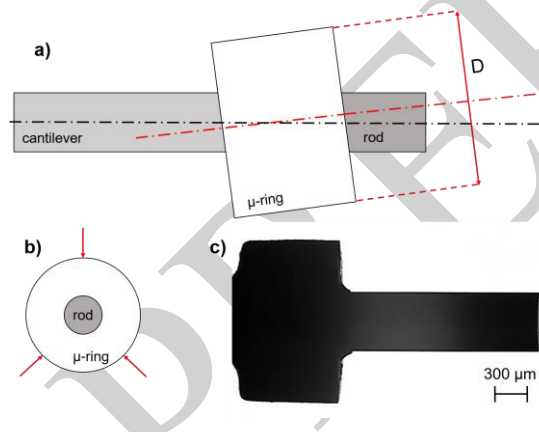


Fig. 3. (a): Measurement scheme. The diameter D and the angle α are indicated. (b) The three circumferential measuring positions. (c) Micro assembly as viewed by the optical CMM.

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 has been considered. This quantity is calculated as:

$$\Delta = \text{Max}(D_i) - \text{Min}(D_i) \quad i = 1, \dots, 3 \quad (1)$$

and it has been defined in parallel to the roundness [9]: a large value of Δ corresponds to low roundness while a low value of Δ describes a micro ring with a high

roundness.

It must be stated that the mold cavities have not been measured because of production reasons. Thus being the real mold cavity diameters unknown, the measured D cannot directly be compared with the nominal $\varnothing 1.50\ \text{mm}$ shown in Fig. 1.

3. Results and discussion

The measurements of the three outputs have been analyzed in order to investigate the process parameters effects. Firstly, it has been statistically verified that the cavity has no effect on D , α and Δ by using the Analysis of Variance (ANOVA). Thus, the two cavities have not been 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 .

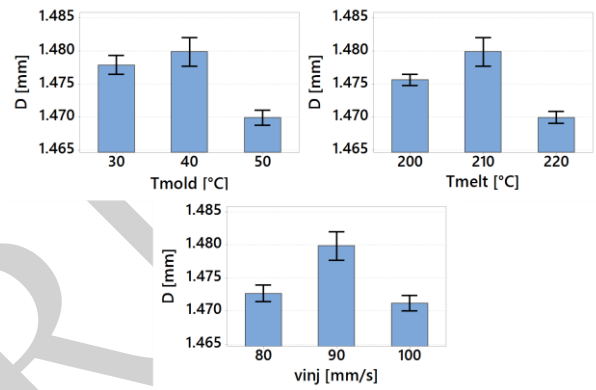


Fig. 4. Interval plots of D . The error bars calculated among the different parts are shown.

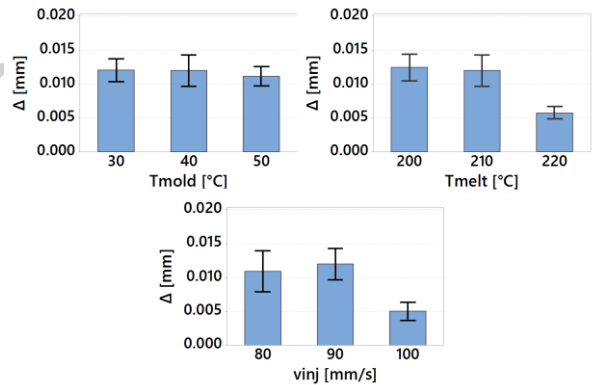


Fig. 5. Interval plots of Δ . The error bars calculated among the different parts are shown.

In regard to 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 $1.480\ \text{mm}$. 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 may

suggest 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.

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) has been 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 .

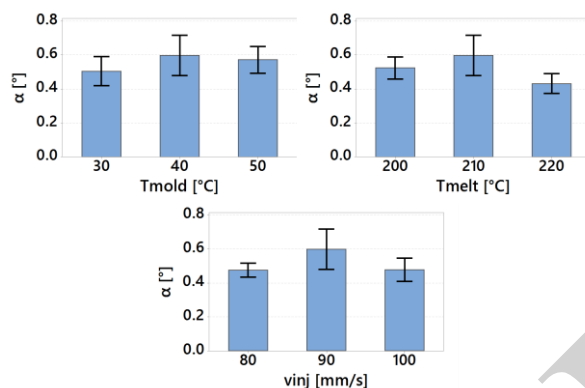


Fig. 6. Interval plots of α . The error bars calculated among the different parts are shown.

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 deviation have the same order of magnitude of 10^{-1} . This proves that the alignment of the micro assembly does not depend on the injection parameters of the overmolded part, but most probably on the alignment of the metal substrate inside the mold cavity. It is also important to note that the average angle ranges between 0.4° and 0.6° .

In order to further assess the alignment of the component, the whole population of measured angles has been 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) have been taken into account. The tested hypotheses were: " $H_0: \mu_\alpha \geq 1^\circ$ " and " $H_0: \mu_\alpha < 1^\circ$ ", being μ_α the mean of the α population. The null hypothesis H_0 has then been 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 has been verified.

4. Conclusions

The micro injection molding process of a micro overmolded multi-material component has been investigated in this work. The effect of three process parameters on three critical geometrical features has been 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 has been 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 has been calculated for each molded part in order to address the dimensional stability of D . It has been found that the best roundness was achieved with the high levels of T_{melt} and v_{inj} , while T_{mold} did 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 has been observed on this geometrical characteristic. This strongly suggests that it mainly depends on the accuracy of the metal substrate alignment inside the micro cavity. The mean value of α has then been tested through a t-test, proving that a tolerance of $\pm 1^\circ$ would be consistently respected and that hence the misalignment assumes on average an acceptable value.

Future studies will be dedicated to the investigation of 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 as well as shrinkage and warpage of the overmolded part.

Acknowledgements

This research work was undertaken in the context of MICROMAN project ("Process Fingerprint for Zero-defect Net-shape MICROMANufacturing", <http://www.microman.mek.dtu.dk/>). MICROMAN is a European Training Network supported by Horizon 2020, the EU Framework Programme for Research and Innovation (Project ID: 674801).

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