PRECISION MANUFACTURING OF THERMOPLASTIC ELASTOMER MICRO RINGS

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INTRODUCTION

The result of the current trend towards product miniaturization is a demand for advances in micro-manufacturing technologies and their integration in new manufacturing platforms.
Micro injection molding (µIM) is one of the most suitable micro manufacturing processes for flexible mass-production of multi-material functional micro components. The µIM can deliver sub-100 mg down to few mg polymer components, with achievable dimensional tolerances in micrometer range. However, in order to achieve such process capabilities, µIM poses great challenges in terms of quality control of both the manufacturing process and the products itself. Shot sizes down to 100 mg and even lower than 10 mg, dimensional tolerances in the micrometer range and surface roughness in the sub-µm range call for process control systems and metrology solution with very low relative uncertainties (<0.1-1%) [1].

The mass-replication nature of the process calls for fast monitoring of process parameters and product geometrical characteristics. In this direction, the present study addresses the possibility to develop a micro manufacturing platform for micro assembly injection molding with real-time process/product monitoring and metrology. The study represent a new concept yet to be developed with great potential for high precision mass-manufacturing of highly functional 3D multi-material (i.e. including metal/soft polymer) micro components.
Towards a fully automated phono cartridges production (see *FIGURE 1a*), the current study focus on the optimization of the thermoplastic elastomer (TPE) suspension ring (see *FIGURE 1b, 1c*) micro injection molding production, as key components for final product functionalities. Specifically, the optimization study is focused on establishing the correct metrology strategy to be later implemented as program routine to control quality of the produced micro rubber rings. The study proves the importance of using tool geometries as reference calibrated artefacts to establish the correct process windows for optimal part quality within tolerance limits in the micrometer dimensional range.

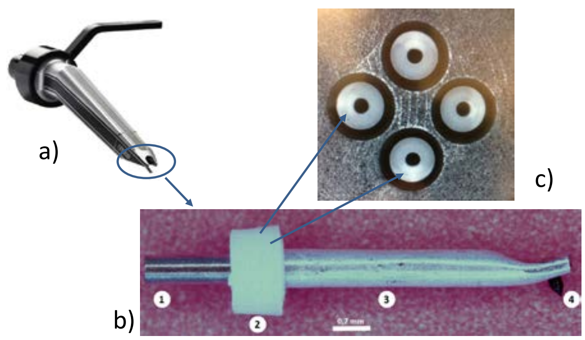

FIGURE 1: a) high performance DJ cartridge, b) (b-1) magnet (b-2) TPE suspension ring (b-3) Aluminum cantilever (b-4) Diamond tip; c) 2D visual inspection of produced suspension rings.

CASE STUDY – PHONO CARTRIDGES

Micro assembly of three-dimensional miniaturized components is of difficult realization due to the reduced dimensions, and hence mass, of the components, and the raising of adhesion forces due to scale effects. The required positioning in the µm/sub-µm precision is also challenging to achieve if top-down approaches when downscaling mechanical assembly systems are applied. In order to overcome these limitations, the ability of polymers to flow around pre-assembled and positioned miniaturized inserts in a micro mold cavity can be exploited by the implementation of micro insert molding [2]. To achieve this final goal, a the first µIM mold prototype that replaced the time consuming through-thickness hot embossing process was designed with the aim of realizinf a high throughput production of micro rings with no preassembled magnet and aluminum cantilever (figure b-1,b-3) inside the mold during injection. The developed mold, figure 2, consists of a three-plate system with a moving middle plate. Two pneumatic pistons push the middle plate forward on each side when the mold is being opened. When the mold closes the ejection side is pushed against the middle plate, where four tapered guides ensures consistent alignment. The closing forces provided by the ejection side overcomes opening pressure form the pneumatic pistons and the middle plate mates with the injection side. The suspension ring has an outside target diameter of 1500 ± 10 µm, inside target diameter of 450 ± 20 µm. When assembled it holds in place the preassembled aluminum cantilever, magnet and diamond tip as seen in Figure 1b.

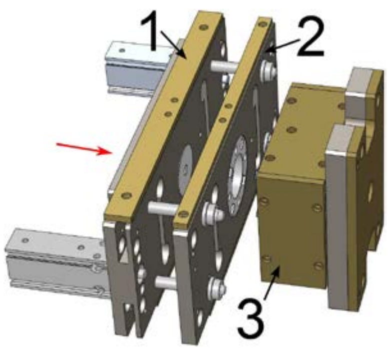

FIGURE 2: Exploded mold view. Red arrow indicates Injection side, 1: Injection plate, 2: moving middle plate and 3: ejection side plate.

MICRO INJECTION MOLDING

To evaluate the influence of process parameters on the replication of the inner and outer ring diameters, a statistically designed set of experiments was carried out. The micro injection moldings were executed on Witmann-Battenfeld Micro Power 15 with an injection unit consisting of an Ø14 mm screw for plasticization and metering combined with a separate Ø5 mm injection plunger. After screening experiments on which different process parameters were varied to find the optimal process window a designed set of experiment (DOE) was performed. A full general factorial design ($2x3^2$=18 experiments) was run.

TABLE1: DOE process parameters.

Process parameters	Values
Melt Temperature [ºC]	210, 220
Injection Speed [mm/s]	60, 80, 100
Packing pressure [bar]	300, 400, 500

Generally, process parameters were set to optimize the resulting quality of the produced geometries considering machine capability, material physical properties and process feasibility. In this respect, three process parameters were identified, after screening experiments, as the most significant affecting final parts quality. Different levels of the melt were chosen in accordance with the material supplier specifications, as a balanced value to avoid material degradation and premature solidification during the filling of the cavity. Injection speeds were selected to enhance replication, bearing in mind the possibility to yield, with a too high speed, high internal stresses, air entrapment and flashes. Finally, packing pressure different levels were selected as trade-off between acceptable shrinkage compensations, dimensional accuracy automatic and effective part demolding.

For each experimental process setting within the designed set of experiments 50 parts were produced to obtain part quality repeatability due to machine stability. After process stabilization 50 parts were collected for each experiment and only 5 parts randomly picked and measured.

MEAUSEREMNT STRATEGY

Dimensional quality control of the produced polymer parts was carried out using a focus variation microscope. The instrument selection allowed for off-line part quality detection, figure 3a, after suspension rings were produced. Future development foresee the same image elaboration technique for in line capabilities. The suspension ring were placed with the gate pointing up in order to secure a plane contact surface on the movable instrument stage. For each suspension ring three measurements repetitions to quantify the polymer rings inner and outer diameter were performed as described in Figure 3b.

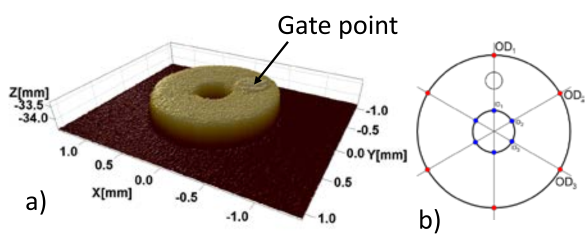

FIGURE 3: a) 3D captured image of TPE suspension ring; b) measurement strategy adapted to dimensionally characterize produced rubber rings.

A DeMeet 220 Optical Coordinate measuring machine was employed to measure/calibrate mold cavities (outer suspension ring diameter) and pin diameter (inner suspension ring diameter).

Measuring uncertainty was calculated following ISO 15530-3 [3]. The expanded standard uncertainty was calculated as:

$$U = k \cdot \sqrt{u_{cal}^2 + u_p^2 + u_w^2 + u_{wt}^2 + u_b^2}$$

Where U = Expanded uncertainty including confidence level. k = Coverage factor of 2 for a confidence level of 95,45%. u_{cal} = Standard uncertainty associated with uncertainty of the calibration of the calibrated workpiece stated in the calibration certificate (Type B evaluation). u_p = Standard uncertainty associated with the measurements procedure, repeated of mold cavities were used to give a more reliable results that reflect the actual measurement procedure (Type A evaluation). u_w = Standard uncertainty of workpiece form error, estimated as max - min of repeated measurements inner and outer mold diameter (Type B evaluation). u_{wt} = Standard uncertainty associated with the variation of workpiece due to thermal expansion which is considered negligible as described in [4]. u_b = Standard uncertainty associated with systematic error from calibrated reference circle (Type B evaluation).

Parameter	ID	OD
Std. Unc. Calibration: u_cal	0,3	0,3
Std. Unc. Measuring procedure: u_p	0,71	0,83
Std. Unc. Systematic error: u_b	0,16	0,05
Std. Unc. Workpiece (form error) : u_w	0,77	1,18
Expanded Uncertainty (95% (k=2)): U	2,2	2,9

TABLE 2: Uncertainty contributions (unit: µm)

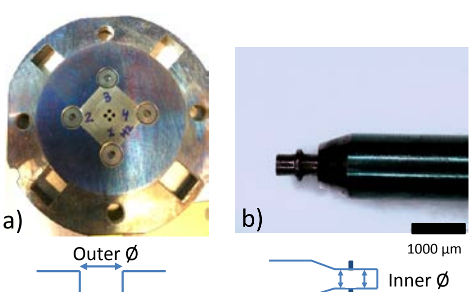

FIGURE 4: a) Mold plate containing 4 cavities; b) pin entering the cavity during injection molding production of the suspension ring.

DISCUSSION AND RESULTS

Inner and outer diameter of the produced rubber rings of each DOE experimental setting were measured using an infinite focus variation microscope enabling the 3D reconstruction of all the fabricated parts. Dimensional measurements analysis of outer diameter (OD) and inner diameter (ID) are shown in the form of main effect plot in figure 5 and figure 6. Error bars in figure 5 and 6 indicate experimental measurement uncertainty calculated including instrument calibration, measurements repeatability and process reproducibility.

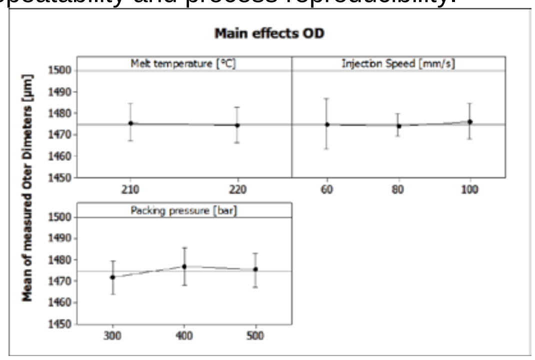

FIGURE 5: Main effect plot of measured suspension rings Outer Diameters.

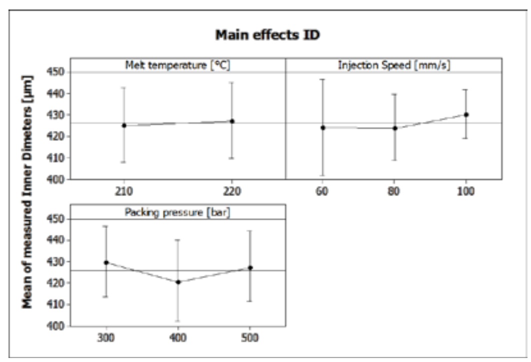

FIGURE 6: Main effect plot of measured suspension rings Inner Diameters.

Significant effects cannot be observed within the tested process windows due to the large measured products variation. Nevertheless, measurements on ring´s outer diameter (figure 5) have shown considerably less product variation compared with internal diameters measured on the equivalent suspension rings. Injection speed was the factor mostly affecting the product variation. Lower level of injection speed (60 mm/s) produces the largest internal diameter variations with extreme values within ± 20 µm. Also, in correspondence to the lower level of injection speed the outer diameter largest variation (± 12 µm) was measured. Parts quality conformance within tolerance limits was carried out using the measurements results from the experimental DOE. Effects of the different process settings (18 DOE experiments) quantified for the produced TPE suspension rings were compared with target design dimensions (i.e. mold technical drawings) and calibrated measurements carried out on the mold, figure 7 and 8. Both histograms showed that if ID and OD of the produced parts within the investigated process windows are compared with target design dimensions, part conformance assessment could lead to wrong results.

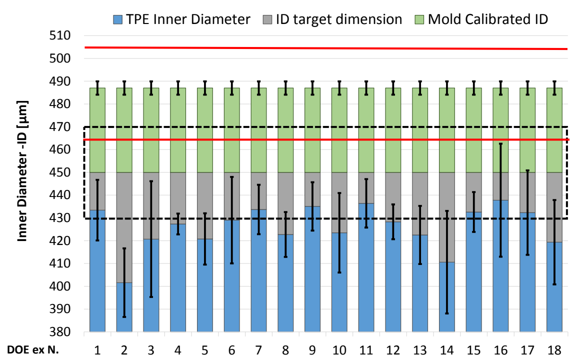

FIGURE 7: Quality conformance assessment of TPE micro rings. Error bars on TPE ID indicate experimental measuring uncertainty. Error bars on the calibrated ID pins dimension indicate expanded uncertainty U=2,2 µm.

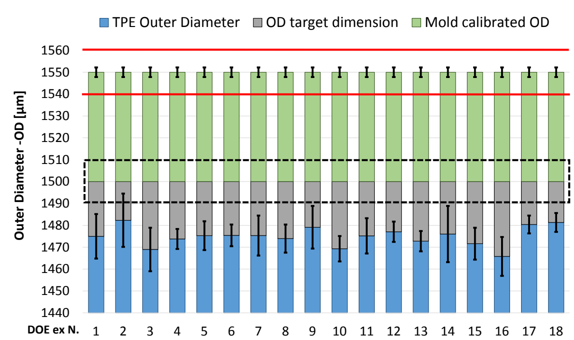

FIGURE 8: Quality conformance assessment of TPE micro rings. Error bars on TPE OD indicate experimental measuring uncertainty. Error bars on the calibrated OD mold cavities dimension indicate expanded uncertainty U=2,9 µm.

In fact, in both diagram the dotted rectangular areas indicate the theoretical tolerance limits of ID and OD (± 20 µm and ± 10 µm respectively) which lead to the conclusion that parts are produced close to the optimal process window yielding part quality within tolerance limits. Even more, looking at this lower section of the histograms wrong conclusion could be made if polymer shrinkage behavior was investigated for future part dimensioning related to shrinkage compensation. Finally, comparing the produced suspension rings (ID and OD) with the real mold features dimension, upper section of the histograms, it is possible to observe that almost none of the experimental process setting produce part that are within the tolerance range (red lines) specified by the manufacture to provide the required functionalities.

CONCLUSIONS

In the present study an approach for micro injection molded TPE micro rings production optimization has been investigated. A design of Experiment was run to identify the most influential process parameters affecting product part quality. Injection speed of 60 mm/s was identified as the parameter that drastically increases the product dimensional variation. Maximum dimensional variation of ± 20 µm was quantified for suspension rings ID. Moreover, based on experimental setup, the present study demonstrate the importance of calibrating master feature in the produced mold to ensure correct product quality acceptance within product tolerance limit.

ACKNOWLEDGEMENTS

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REFERENCES

[1] Hansen H.N., et. al. Dimensional Micro and Nano Metrology, CIRP Annals Manufacturing Technology. 2006 55(2):721-743.

[2] Michaeli W, et.al. Micro assembly injection moulding Microsyst Technol. 2006, 12: 616- 619.

[3] International Organization for Standardization (ISO). Geometrical product specifications (GPS) - coordinate measuring machines (CMM): Technique for determining the uncertainty of measurement - part 3: Use of calibrated workpieces or measurement standards (ISO 15530-3:2011), 2011.

[4] Tosello G., Hansen H.N., Gasparin S.et. al., Applications of dimensional micro metrology to the product and process quality control in manufacturing of precision polymer micro components, CIRP Annals, 2009, 58:467-472.