High accuracy and precision micro injection moulding of thermoplastic elastomers micro ring production

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Abstract

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 moulding with real-time process/product monitoring and metrology. The study represents 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. The activities related to HINMICO project objectives prove the importance of using tool geometries as reference calibrated artefacts to establish effective process technology development and control. The results allow identifying the correct process windows for optimal part quality reducing product dimensional variation in the micrometer dimensional range. The proposed metrological approach enabled to quantify product dimensional variations based on process and tooling capabilities.

Keywords: Micro injection moulding, optical metrology, process quality control development.

1. Introduction

In recent years, the manufacturing industry and the society as a whole have witnessed a rapid increase in demand and usage of micro-products and micro-components in many industrial sectors such as electronics, medical, biotechnology and automotive [1][2]. As a result of the current trend towards product miniaturisation, there is a demand for advances in micro-manufacturing technologies and their integration in new manufacturing platforms. The research on the downsizing of the injection moulding has generated a new process technology, micro injection moulding (μIM) [3], capable of micro manufacturing on a mass production scale both one-component and multi-material micro components [4] characterized by multidimensional scale integration, high accuracy with tolerances in the micrometer range [5]. Injection moulding of micro components 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%) [6][7]. 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 moulding with real-time process/product monitoring and metrology. The study represents 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. HINMICO project activities have been focus towards these directions. The present paper reports about the optimization of the thermoplastic elastomer (TPE) micro injection moulding process as key components for final product functionalities of a high-performance phono cartridges. Towards total quality production a metrological approach identified as a key enabling technology for future real-time process/product quality monitoring was introduced. The present paper discuss the possibility of controlling effects of different process settings on critical product characteristics with the micro ring production as reference as a measurable linking either process variation (tool characteristics) performances with material behaviour during and after μIM.

2. Micro injection moulding of TPE suspension rings

To evaluate the injection moulded TPE suspension rings a benchmark study was initially carried out to qualitatively characterize the produced suspension rings. Opening experiments were run with process parameters listed in table 1. The first batch called “data sheet” utilizes the process parameters recommended by the TPE material supplier. The second produced batch called “high” employed temperatures and pressures values levels greater than the recommended one to observe possible effects on rings replication. The third batch called “low” employed pressures values levels lower than the recommended one to observe possible effects on rings replication. Finally the process settings of the “improved” batch were found as part of an operational optimization process that led to achieve better filling and smaller to no defects on the produced parts. This optimization was based on manual inspection under an optical microscope.

2.1. Scanning Electron Microscope inspection

From the top view of Fig. 1 the suspension rings looks well formed, with a small wad line. The gap residual mark is small and does not protrude from the...
surface which is important due to the mounting of the suspension ring in the stylus housing. A large defect is present at the circumference of the inner diameter at the weld line position most probably caused by entrapped air pushed against the pin-core.

Table 1: Process parameters for the investigated production batches

<table>
<thead>
<tr>
<th>Process parameters</th>
<th>Data Sheet</th>
<th>High</th>
<th>Improved</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melt Temperature (°C)</td>
<td>185</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>Mould Temperature (°C)</td>
<td>40</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>Clamping Force (kN)</td>
<td>180</td>
<td>180</td>
<td>210</td>
</tr>
<tr>
<td>Injection speed (mm/s)</td>
<td>120</td>
<td>200</td>
<td>85</td>
</tr>
<tr>
<td>Ejection speed (mm/s)</td>
<td>200</td>
<td>200</td>
<td>200</td>
</tr>
</tbody>
</table>

From the cross-section it can be seen how there is a misalignment between the pin-core and the ejector tube, which gives a countersink around the centre hole. The internal geometry does not look very well defined especially toward the ejection side. It is also worth noticing that the corner of the outside diameter at the ejection side very well defined with a small rounding compared to internal corner of the cavity. This difference is probably due to the tooling process and the inside of the ejector tube, which is possibly due to entrapped air pushed against the pin-core.

A flash has started to occur in between the pin-core and the inside of the ejector tube, which gives a countersink around the centre hole. The internal geometry does not look very well defined especially toward the ejection side. It is also worth noticing that the corner of the outside diameter at the ejection side very well defined with a small rounding compared to internal corner of the cavity. This difference is probably due to the tooling process and the inside of the ejector tube, which is possibly due to entrapped air pushed against the pin-core.

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The qualitative analysis indicated that high pressure and injection speed of the high batch fills the cavity well, but gives problems with defects caused by entrapped air. Air trap defects were also detected for the data sheet batch indicating that clamping force was the most influencing process parameter affecting the weld lines depth. The correlation between the low clamping force and small weld line defects could be explained by the increased air evacuation at the mould split line as a consequence of the lower clamping force. Although this explanation is plausible no investigations were conducted in order to fully support this relationship.

2.2. Part mass variation

One method of monitoring the process variation is to look at the consistency of the part mass. This has been done for the produced TPE suspension rings. 50 parts for each batch were measured and different mass distribution plotted in Fig. 4. The smallest mass deviation is obtained using the improved process settings with a low clamping force that allow for better air evacuation compared to other TPE batches as seen in the SEM quality inspection. Results also indicate that it is possible to increase the density of the TPE material by using high processing temperatures and pressures. The density increase influences the damping properties of the material enabling the possibility to produce within the same material compound suspension rings with slightly different damping properties for different types of cartridges.

2.3. Simulation and experimental comparison

This investigation aimed at studying the development of weld line formation due to air entrapped during polymer filling of the cavity, Fig. 5. The simulation was capable of predicting the location of the entrapped air that causes the parts defects. Main interest of the numerical product quality optimization was to consequently minimize these defects as much
as possible in order to ensure uniform damping properties, so that the mounting orientation of the suspension and the vibration direction of the cantilever will not influence the acoustic properties of the finished cartridge. The comparison between simulations and the SEM pictures have shown that all air entrapments occurring at positions that are in contact with mould part lines are reduced to very small weld lines due to the capability of the air to evacuate the cavities through the parting line. At positions where the air cannot escape through any parting lines, defects and surface imperfections develop compromising component functionalities. Generally, the simulations confirmed that bigger weld lines are generated towards the inner cylinder section of the rings as outlined by the SEM pictures [9].

![Figure 4](image4.png)

Figure 4: Comparison of part mass distribution for the different production batches. Data sheet batch (avg. value = 2, 28 mg ± 0,16 mg). High batch (avg. value = 2, 46 mg ± 0,16 mg). Improved batch (avg. value = 2, 23 mg ± 0,09 mg).

![Figure 5](image5.png)

Figure 5: The filling behaviour during the merging of the two flow fronts is broken into six pictures.

2.4. Dimensional weld line investigation

Reliable quantification of the weld line is not currently available as output analysis of the numerical software. Dimensional measurements of the weld line depth was performed using a focus variation optical microscope ensuring single acquisitions time lower than production cycle time. Measurement results have shown a direct correlation between tested process parameters and weld line dimensional variation. Larger weld line depth variation was quantified for the rings produced with higher clamping force and injection speed. The results dimensionally quantified the effect of air entrapped into the mould cavity on the final replication quality of the TPE components [10].

3. Effective product and process control

A further optimization study was carried out with focus on effective process control based on final part dimensional variation. A statistically designed set of experiments was carried out. The micro injection moulding experiments were executed on Wittmann-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. Following results obtained in the preliminary studies on which parts defects were minimized as a function of improved final product performances, process parameters, table 2, were tested during the experimental micro injection moulding phase. 5 repetitions of a full general factorial design (2⁷x4 (cavities) = 144 experiments) were run. Table 2: DOE process parameters.

<table>
<thead>
<tr>
<th>Process parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melt Temperature [°C]</td>
<td>30, 40</td>
</tr>
<tr>
<td>Injection Speed [mm/s]</td>
<td>60, 80, 100</td>
</tr>
<tr>
<td>Packing pressure [bar]</td>
<td>150, 200, 250</td>
</tr>
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![Figure 6](image6.png)

Figure 6: a) Mould plate containing 4 cavities; b) pin entering the cavity during injection moulding production of the suspension ring; c) mould cross section schematic view.

Measuring uncertainty was calculated following ISO 15530-3 [11]. Measurement results are reported in table 3.

Table 3: Mould cavities/ basename calibrated values. Single values indicate average values of 10 different measurements for each inner and outer diameter. Us and Uc indicate Expanded Uncertainty values in μm.

<table>
<thead>
<tr>
<th>Cavity</th>
<th>Outer Diameter (OD) [mm]</th>
<th>u₀</th>
<th>Inner Diameter (ID) [mm]</th>
<th>u₀</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cavity 1</td>
<td>1550.6</td>
<td>482.1</td>
<td>1555.1</td>
<td>482.7</td>
</tr>
<tr>
<td>Cavity 2</td>
<td>1551.6</td>
<td>482.7</td>
<td>1555.1</td>
<td>482.7</td>
</tr>
<tr>
<td>Cavity 3</td>
<td>1549.1</td>
<td>482.3</td>
<td>1555.1</td>
<td>482.4</td>
</tr>
<tr>
<td>Cavity 4</td>
<td>1555.1</td>
<td>482.4</td>
<td>1555.1</td>
<td>482.4</td>
</tr>
</tbody>
</table>

The reference diameter (d) calculated in Eq. 1 allow to effectively evaluate the different polymer shrinkage directions Fig. 8b of inner and outer diameters (OD, ID) in respect of calibrated mould dimensions. Correct shrinkage quantification directly relate to final assembled cartridge (Fig.7) sounds quality. TPE micro rings critical geometries were selected as product quality output indicator based on final product assembly tolerances contains.
4. Conclusions

The mass-replication nature of the process calls for fast monitoring of process parameters and product geometrical characteristics. In this direction, the present study reported the development and its production of high accuracy and precision micro injection moulding of thermoplastic elastomers micro rings. The critical factors in µm process related to injection speed, mold temperature, clamping force, surface replication and simulation accuracy have been presented. The study represents 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. The results prove the importance of using tool geometries as reference calibrated artefacts to establish effective product quality control and process monitoring development. In light of the produced results based on dimensional part verification expressed as product variation from a geometrical reference system process and tool accuracy were verified.

Acknowledgements

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References

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