Application of different process chains for polymer microfluidics fabrication including hybrid tooling technologies, standardization and replication: a benchmark investigation within 4M Polymer Division

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Abstract

This paper is based on the Division 4 “Processing of Polymers” activities within the 4M NoE “Multi-Material Micro Manufacturing”. To overpass limitations of the current existing micro tooling capabilities, a new generation of micro hybrid tooling technologies for micro replication was developed. A metrological approach was applied to standardize the employed tooling processes ($\mu$-milling, $\mu$-EDM, laser $\mu$-machining, electrochemical $\mu$-milling). The micro tools were then tested with different polymers. The paper provides a comparison of these technologies concerning obtainable feature sizes, surface finishing, and aspect ratios of both micro tools and micro moulded parts.

Keywords: Hybrid tooling, micro tools, micro injection moulding, standardization.

1. Introduction

Micro injection moulding is a replication technology that enables large scale production of polymer-based micro products. The injection moulding of polymer micro components represents a challenge in terms of process realization and optimization. On the other hand, micro injection moulding requires tooling technologies providing high performances in terms of dimensional accuracy, surface finishing, aspect ratio and three-dimensional feature size miniaturization. In order to exploit the design of freedom given by fabrication process such as injection moulding, high performance micro tools have to be fabricated.

The current existing micro tooling technologies present limitations in terms of smallest obtainable feature size, removal rate, accuracy, surface finishing, etc. To overpass these bottlenecks a new generation of micro hybrid tooling technologies have been established within the Polymer Division of the European Platform 4M Network of Excellence “Multi-Material Micro Manufacturing”.

2. Micro tooling technologies

Micro machining processes currently employed for the manufacturing of micro moulds show limitations [1]. Micro milling is problematic with sizes below 0.1 mm in tool steels, and repeatable feature sizes below 50 $\mu$m (even with the newest 40 $\mu$m tools for milling and drilling) are not possible. Smaller tools down to 20 $\mu$m are also available but are limited to drilling and with low quality in the cutting edges.

Wire-EDM (Electro Discharge Machining) with thin wires, smaller than 50 $\mu$m (20-30 $\mu$m), allows better accuracy and surface roughness but is limited to ruled geometries. Micro-die sinking EDM is also very problematic for obtaining features sizes below 50 $\mu$m, and the roughness is still poor for replication purposes.

Micro EDM milling is a promising new technology in the field of EDM [2,3]. Flexible and suitable for three-dimensional feature machining, the process needs investigation in order to assess parameters for electrode wear compensation. Electrode diameters down to 15-20 $\mu$m can be obtained by means of a micro wire-EDG (Electro Discharge Grinding) unit.

Laser milling is most suitable for machining parts with one-sided geometry or for partial machining of components from one side only. Complete laser milling of parts is also possible but difficulties in accuracy of re-positioning for additional set-ups have to be addressed. The influence of the process parameters is complex and must be optimized to obtain the highest part quality.

A new technology called electrochemical micro milling (ECF, where F is the German acronym for milling) has been recently introduced to machine hard materials like stainless steel and other electrochemical active materials. Feature dimension below 50 $\mu$m have been obtained [4]. The very small removal rate (as low as 6x10$^{-9}$ mm$^3$/min) allows high resolution in machining and therefore is suitable to manufacture the finest details in a pre-machined structure.

Clearly, with the increasing of miniaturization and integration of different micro features, only a combination of processes can lead to an accurate
The concept of hybrid tooling is therefore introduced. Hybrid tooling can be defined as “the capability of producing a mould insert combining two or more processes in sequence”, i.e. on the same process chain for tooling [5].

3. Application of hybrid tooling

In order to investigate the feasibility of application of micro machining processes to hybrid tooling technologies a micro fluidic device have been chosen (see Fig. 1). Its functionality is of separating blood cells and plasma due to the micro channel bend structure design [6]. Critical dimensions and tolerances required by this geometry were the following:

- Channels 20, 50, 75 µm wide (tolerance ±5 µm);
- Radius down to 25 µm (tolerance ±5 µm);
- Depth of 100 µm (tolerance ±5µm);
- Sub-micrometer roughness (suitable for micro fluidic applications) (Ra≤100nm).

3.1. Tooling strategies

Five inserts have been produced, based on the same geometry, using the following different tooling strategies:

- µTool_1 = direct tooling with an optimized 4 steps micro milling operation (insert material: Stainless Steel AISI 304) (see Table 1);
- µTool_2 = direct tooling with an optimized 4 steps micro milling operation (insert material: tool steel EN30B) (see Table 1);
- µTool_3 = indirect hybrid tooling with µEDM milling of silicon, deposition of nickel-copper by electroforming, selective silicon substrate etching, final cut by µWire-EDM (insert material: nickel with copper substrate) (see Table 2);
- µTool_4 = direct hybrid tooling with micro milling and ECF (insert material: Stainless Steel 1.4441) (see Table 2);
- µTool_5 = direct hybrid tooling with micro milling (see µTool_2) and laser milling (insert material: tool steel EN30B) (see Table 2).

Direct machining refers to tooling technologies for the manufacturing of the negative geometry (i.e. creation of the tool's geometry). In this way, when the replication process is carried out (i.e. injection molding), the positive geometry represented by the plastic part is produced. The term indirect machining covers the fact that the master structure produced by machining is the positive geometry, which is identical in shape to the final product (i.e. the opposite of what is needed for the actual mold insert) [7].

Two of the main issues of the micro structure to be machined were to produce the 25 µm radius and to manufacture the two 20 µm wide ridges meeting the dimensional requirements (width, height, aspect ratio) as well as having the walls straight with no bending involved. With a conventional approach, e.g. direct tooling by micro milling, the smallest obtainable radius is directly related to the minimum micro mill diameter available (100 µm) as shown in Fig. 2 for both the micro mold and the micro molded part. On the other hand, hybrid technologies can provide a viable solution to decrease the smallest obtainable dimension of micro structure (see Fig. 3 and 4).
To obtain the required 20 µm ridges different approaches were used. When micro milling was employed, an optimized procedure for thin wall milling was applied. Effect of such optimization is visible in Fig. 5. With electrochemical milling, where cutting forces (responsible for walls’ bending) are not involved, straight and thin walls can be manufactured (see Fig. 6, right). With indirect tooling a channel was machined in the master’s substrate and the ridges were manufactured as channels (as it will be in the molded part). The µ-wire EDG technology applied to the µEDM milling machine allowed dressing the electrodes to a diameter down to 15 µm, enabling the manufacture of the required dimensions (see Fig. 6, left).

5. Micro injection molding

A replication benchmarking among the 4M Polymer Division’s partners has been performed. Different injection molding machines (both conventional and micro molding machines) have been employed for replication, as well as different materials, applying a design of experiment approach. Here a few results are shown (see Tables 3 and 4), providing values of surface roughness average Ra and of dimensions which are possible to obtained with the different materials and injection molding machines.

Table 3. Injection molding of micro fluidic system: process parameters and surface roughness measurements.

<table>
<thead>
<tr>
<th>Micro tool</th>
<th>µTool_2</th>
<th>µTool_5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machine</td>
<td>Injection moulding</td>
<td>Injection moulding</td>
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<tr>
<td>Injection unit</td>
<td>Plastication screw</td>
<td>Injection plunger</td>
</tr>
<tr>
<td>Material</td>
<td>COC</td>
<td>PC</td>
</tr>
<tr>
<td>T mould [°C]</td>
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<td>50</td>
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<tr>
<td>T melt [°C]</td>
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<td>250</td>
</tr>
<tr>
<td>Inj. Speed [mm/s]</td>
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<td>900</td>
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<tr>
<td>Ra Pos A [µm]</td>
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<td>Ra Pos A [µm]</td>
<td>0.08</td>
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</table>

Table 4. Injection molding of micro fluidic system: process parameters and dimensional measurements.

<table>
<thead>
<tr>
<th>Micro tool</th>
<th>µTool_2</th>
<th>µTool_3</th>
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<tbody>
<tr>
<td>Machine</td>
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<td></td>
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<tr>
<td>Injection unit</td>
<td>Plastication screw</td>
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<td>Material</td>
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<td>Inj. Speed [mm/s]</td>
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<td>W1 [µm]</td>
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<tr>
<td>W2 [µm]</td>
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<td>W bw 1,2 [µm]</td>
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<td>136</td>
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</table>

6. Results and discussion

Metrological investigations of the different micro tools showed that the required height H1 and H2 of 100µm for the ridges could be met in most cases within a tolerance of 15% (see Fig. 7). A challenge was represented by the ridges width (20µm), which could not be manufactured with a sufficient accuracy. The micro tool 5 was close within an interval of ±20%. The others exhibited ridges of width 40% up to 100% larger than the nominal dimension (see Fig. 8). The area between the two ridges could be machined with good accuracy: the difference in depth (D bw 1,2) was in average of 7µm and the distance of the ridges was manufactured with a tolerance lower than 8% (see figure 9).

The surface roughness was measured in three positions (see Fig. 10) and was in almost all cases below 0.5 µm. The smoothest surfaces have been obtained by micro milling: roughness surface ranges between 0.07 µm and 0.37 µm, with an average value of 0.21 µm. The µEDM milling surface also created...
smooth surfaces (Ra between 0.14 µm and 0.33 µm), but less uniform if compared with the others. In fact, a higher standard deviation from repeated measurements in different areas of the same feature was encountered. The electrochemical milled surface exhibited a quite rough surface (Ra=0.61 µm) if compared with conventional processes.

7. Conclusion

Mass fabrication of polymer based micro product is directly connected to the availability of accurate and reliable micro tooling technologies. The decrease of dimensions of micro features, higher aspect ratio, sub-micrometer surface roughness challenges the existing machining technology. Hybrid micro tooling technologies, i.e. combination of different micro machining processes, have been presented as possible solutions to overpass limitations of the current existing micro tooling capabilities. Metrology of micro components is the tool to achieve standardization of the presented technologies and provides the basis for reliable comparison, for both tools and injection molded parts.

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References