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Publication date:
2017

Document Version
Publisher's PDF, also known as Version of record

Influence of Injection-Molding Process Parameters on Part Replication of Microstructures with Additively-Manufactured Soft Tooling Inserts

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Abstract

The objective of this research is to investigate the influence of injection molding parameters on the dimensional replication of microstructure surfaces in injection molding with additively manufactured soft tooling inserts in a photopolymer material. The replication degree of micropillars on injection-molded tine rings was assessed and a Design of Experiments (DOE) approach was used to investigate which factors influence the replication. A full factorial analysis with three factors at two levels lead to the conclusion that a high mold temperature increases the replication degree of the pillar diameter and decreases the replication degree of the pillar height. A high melt temperature increases the pillar diameter independently from the pillar height. A higher injection speed affects both pillar diameter and height negatively. In addition, the study showed a significant difference in the replication degree between inserts on the injection side and the ejector side of the mold respectively. Also, a position closer to the injection gate supports a higher replication degree. Insert wear was found insignificant within the experimental range of up to 100 injection cycles.

Keywords: Additive manufacturing, Injection molding, Microstructures

1. Introduction

Today, tooling is amongst the most important applications of additive manufacturing (AM) technologies [1]. Technical progress in the development of precision AM technologies allows for the introduction of process chains different from conventional production, including subtractive-manufacturing techniques.

The replication of surface geometries at the micro and nano scales is a key aspect in many technical areas involving precision engineering [2]. Injection molding is a suitable technology for the mass production of polymer parts including microstructure.

The advantages of using polymer-based AM technologies as part of an injection molding process chain include low costs and faster tooling [3]. Stereolithography (SLA) and Digital Light Processing (DLP) were successfully investigated for their capability of producing injection-molding inserts at least as early as 1990 [4] and 2007 [5], respectively. In the meantime, a similar additive process called "Polyjet Technology" has been employed in using "Digital ABS as a rapid tooling material for polymer injection moulding" [6]. Recently, DLP has attracted attention for enabling a step closer "toward mass production of microtextured microdevices: linking rapid prototyping with microinjection moulding" [7].

This research focuses on investigating the dimensional precision and surface quality of microstructures reproduced in microinjection molding with inserts manufactured using DLP technology.

2. Materials and Methods

2.1. Design of Test Geometry

The analyzed injection-molded part is based on a geometry used for medical purposes (tine ring [8]) comprising a hollow cylinder (inner diameter 1 mm, outer diameter 2 mm, height 1.5 mm) with four tines (rotational symmetry 90°) attached in an angle of 60° (see Fig. 1).

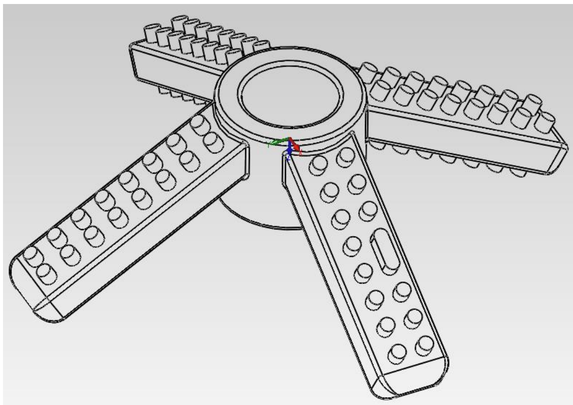

Fig. 1. CAD-model of tine ring with microstructure.

The four tines are 3.5 mm long and have a rectangular cross section of 1 x 0.5 mm^2. On the two opposite surfaces of each tine, a microstructure cylinder pattern is distributed equally (diameter 200 µm, height 200 µm, aspect ratio 1).

2.2. Tooling

The inserts were manufactured in a photopolymer material (HTM140V2) by a printer using DLP technology (Envisiontec P3 Mini Multi Lens).

The cavity was realized by combining two inserts produced with AM: one mounted on the moving side of the mold, the other mounted on the fixed side of the mold. Both inserts contained surface microstructure pattern.

2.3. Injection Molding

The injection molding was performed with an Arburg Allrounder 370A in natural polyethylene (PE Purell 1840). Eight experiments were carried out following a full factorial design of experiments (DOE, three control factors, two levels, see Table 1).

Table 1
Low and high levels of the three Injection molding control factors

	Low (-)	High (+)
Mold Temperature (T_{mold})	30°C	60°C
Melt Temperature (T_{melt})	175°C	185°C
Injection Speed (v_{inj})	38 mm/s	65 mm/s

Since the focus of this research is on the replication of the microstructure and not on the lifetime of the inserts, a maximum of 100 injection cycles were conducted with each pair of cavity inserts unless insert failure occurred earlier. A new pair of inserts was employed for each of the injection molding experiments.

2.4. Part Assessment

The part assessment included metrological investigations using a laser-scanning microscope (OLS4100 Lext from Olympus) at a magnification of 10x.
The produced parts were measured on two different sides of the tine (back and front) at two different positions (near and far from gate, see Fig. 2) which resulted in

$$2^5 = 32 \qquad (1)$$

measurements.

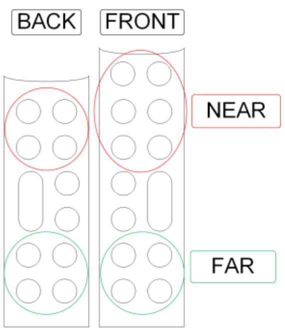

Fig. 2. Front and back side of the marked tines selected for scanning. The scanned tine regions are shown in colored circles. Back (ejector side) and front (injection side).

SPIP™ 6.6.1. from Image Metrology was used to analyze the obtained images. The replication degrees

$$Z = z_{pillar} / z_{hole} \qquad (2)$$

(with Z = replication degree for the pillar height, z_{pillar} = pillar height on the injection molded part, and z_{hole} = depth of the hole in the additively-manufactured insert) and

$$Dia = d_{pillar} / d_{hole} \qquad (3)$$

(with Dia = replication degree for the pillar diameter, d_{pillar} = pillar diameter on the injection-molded part, and d_{hole} = diameter of the hole in the additively-manufactured insert) were chosen to quantify the quality of the injection-molding process and to exclude the variability of the printing process.

3. Results and Analysis

3.1. Inserts

Two core challenges were expected during the printing process. First, warpage of the printed part. This phenomenon could be partly overcome by postprocessing by abrasive machining for fitting the AM inserts into the steel mold block. Second, residual liquid material staying in the printed microholes due to capillary effects and curing over time when being exhibited to daylight. A partial solution to the second challenge is proper cleaning of the part after printing (e.g. repeatedly blowing filtered air onto the surface after bathing the part in isopropanol) to remove as much of the remaining uncured material as possible (see Fig. 3).

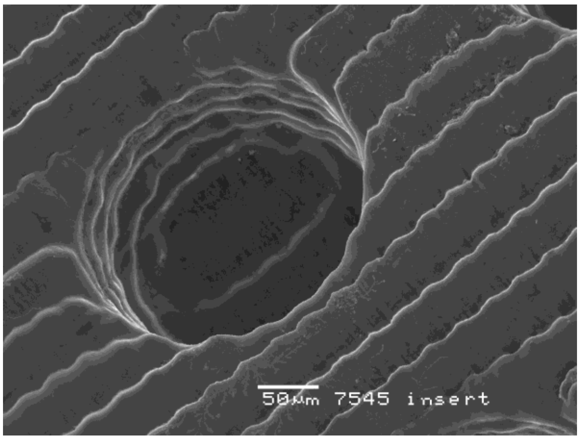

Fig. 3. A properly cleaned 200 µm hole in a printed insert.

3.2. Injection molded parts

An insert made by additive manufacturing, as well as an injection-molded tine ring, is presented in Fig. 4. The microstructure is visible in Fig. 5. Flash is present at the side boarders of the tines which is the result of both low clamping forces to keep the inserts intact and print inaccuracies.

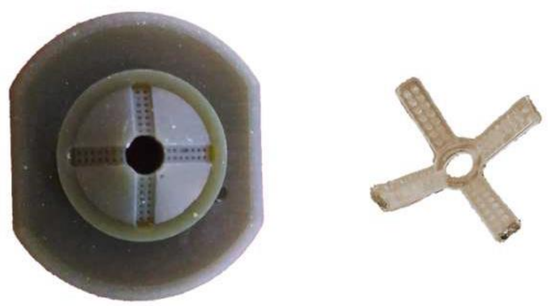

Fig. 4. Micro injection molding inserts (left) and resulting injection molded part (right).

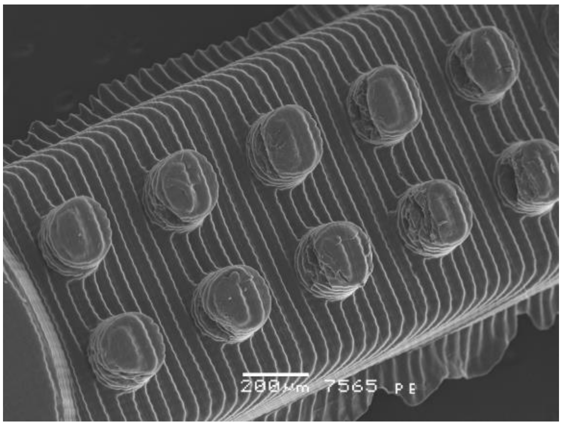

Fig. 5. Microstructure on the surface of the injection molded tine ring.

The dimensions of the microstructures on both insert and injection molded parts were quantified based on a SPIP® analysis (Fig. 6 and Fig. 7) of the laser scanning microscopy images, which is described in detail in [8].

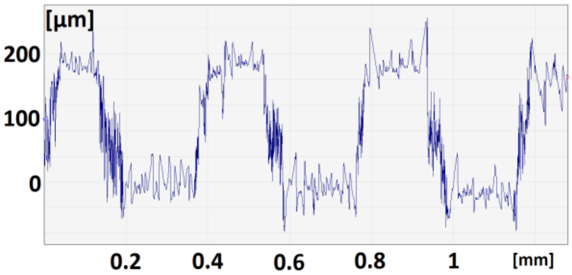

Fig. 6. SPIP® image representing the surface profile along the vertical red line in Fig. 7.

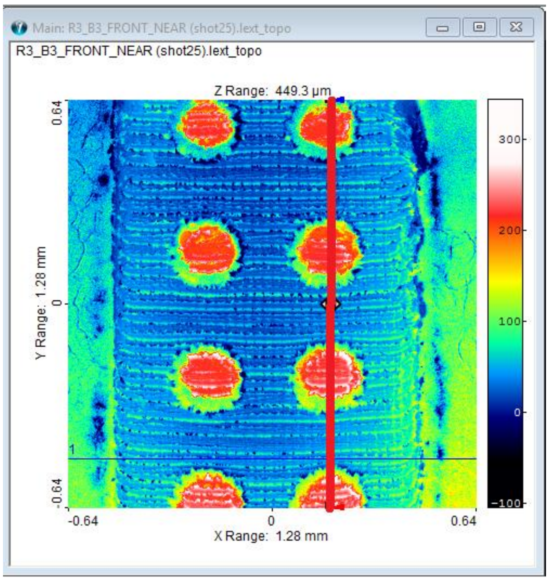

Fig. 7. SPIP® image representing the surface structure of the tine of the injection molded part.

Fig. 8, a main effects plot of the replication degree of pillar height and diameter created with the statistical software Minitab® 17.2.1, shows the analysis of the influence of the injection molding parameters on the pillar dimensions.

It seems that a higher mold temperature leads to slightly increased pillar diameters and decreased pillar heights. A possible explanation is that, due to the higher temperature, the polyethylene is softer when being ejected, resulting in tilted pillars. The laser-scanning microscope cannot detect structures below the tilted pillars and interprets the diameter to be larger than it is.

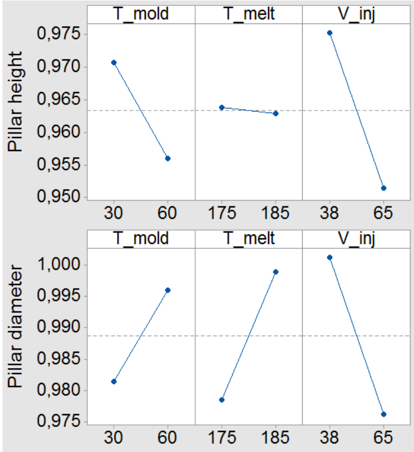

Fig. 8. Influence of the injection molding parameters on the replication degree of the injection molded parts.

A higher melt temperature results in a larger pillar diameter and has a negligible influence on the pillar height. An explanation similar to before is possible in this case. Finally, higher injection-molding speed leads to a decrease in both pillar diameter and pillar height.

However, all tendencies in Fig. 8 are smaller than 2,5 % and therefore not very strong since they are in the same range of measurement and process repeatability.

3.4. Insert failure

During the injection molding, insert failure occurred for some inserts due to crack development and, subsequently, material flowed into the cracks. In the earliest case, this occurred after 20 shots. Slight misplacement of the insert or printing inaccuracies are a potential cause for insert deformation during the mounting on the insert as well as when the mold is closed and high closing forces occur. With its low elongation at break of (3.5%, [9]), more research is necessary to predict the failure modes of inserts printed in this material more accurately.

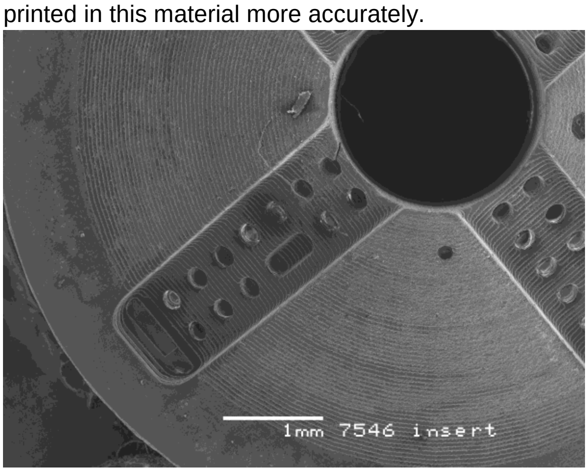

Fig. 9. SEM image of insert with some of the holes stuck with material. The two connected holes are a mark to recognize the tine selected for dimensional analysis.

A local failure mode appeared when material got stuck in the holes either during the print process (photopolymer) or during injection molding (Fig. 9).

3.3. Mold wear

In experiments 3 and 4 (see Table 2), the inserts lasted the whole 100 shots scheduled for each experiments.

Table 2
Levels of the three Injection molding control factors in experiment 3 and experiment 4

	T_{mold}	T_{melt}	v_{inj}
Experiment 3	60°C (+)	175°C (-)	38 mm/s (-)
Experiment 4	60°C (+)	175°C (-)	65 mm/s (+)

The injection molded tine rings were collected in batches of 10 rings each and used for an additional investigation on mold wear. The analysis of the pillar height of the tine rings at the far back position shows no indication of mold wearing influencing the dimensions of the injection-molded parts (see Fig.10).

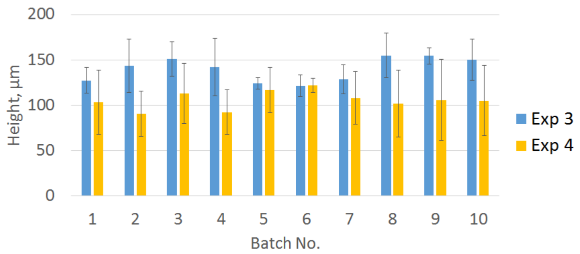

Fig. 10. Pillar height at the far back position in experiments 3 and 4 over 100 shots (error bars = standard deviation).

The line pattern that resulted from the layer thickness of the printing process is also present on the injection molded parts (Fig. 5) and is therefore a potential obstacle for the microstructure during ejection. Inserts printed with smaller layer thickness and better print resolution should be analyzed for the influence of these parameters on this phenomenon.

4. Conclusion

This research shows that the polymer-based, additive manufacturing technology DLP represents a potential option for manufacturing injection-molding inserts with microstructured surfaces, thereby modifying significantly the tooling part of the conventional injection-molding process chain.

A tine ring geometry with 200 x 200 µm pillars (aspect ratio=1) was assessed in a 3x2 full factorial design in an injection-molding experiment in PE. Although the molded microstructures can be affected by print inaccuracies (partly filled holes due to capillary effects), the observed replication degrees of the microstructure are quite high with values between 0,95 and 1. The replication degrees appear quite indifferent (smaller than 2,5%) to the modification of the injection molding parameters presented in this paper. Mold wearing showed no influence on the pillar height over a period of 100 shots in the experiments assessed for that phenomenon.

For future research, it is suggested to:

- investigate the influence of mold temperature on insert life time and to perform thermal simulations of the cooling process as well as to
- use mold materials with a higher “elongation at break” material parameter for their reduced sensitivity to the high forces occurring during the clamping of the mold as well as the injection molding process
- repeat the experiment with carbon fiber reinforced HTM140, a concept introduced in [10] leading to a significantly longer mold life time, to quantify the influence of the fibers on the replication degree as well as the change of the replication degree over a much higher number of parts produced with one pair of inserts.

Acknowledgements

The research presented in this paper was carried out in the framework of a project between Technical University of Denmark (DTU) and Neurodan A/S, Aalborg, Denmark, financed by the High Technology Fund (HTF), Denmark.

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