A study on the mouldability of POM microdetails in moulding blocks using micromanufacturing technologies

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Abstract

The integration of micro fabrication and micromoulding techniques contributed to the massification of microsystems in several domains of activity at feasible costs. In this study the mouldability of microdetails generated by microEDM, micromilling and laser milling in microinjection moulding blocks is assessed. For that purpose, a polyacetal for precision microparts is used to evaluate how microfeatures are replicated in microinjection moulding. The mouldings were produced in a instrumented micromould with two interchangeable moulding blocks, enabling the test of various mould inserts. The processing conditions were simulated with the Moldex3D commercial software. Despite the commercial success of microinjection moulding, the process involves microscale phenomena that make the polymer flow different from the conventional flow at the macro scale. The microinjection tests and the simulation allowed the gathering of knowledge to incorporate on mathematical models and simulation software, enabling the filling simulations at this scale being more accurate. Further to the assessment of the microdetails mouldability, the surface replication and finishing of the mouldings were analysed by optical and SEM microscopy.

Introduction

There has been a significant increase in the application of miniature components and availability of microtechnologies in recent years. The main driver of this trend was mainly the electronics industry requiring smaller and smaller components and effective manufacturing processes. Until recently, the production of this miniature parts was focused on technologies traditionally used in the world of electronics and semiconductor industry, like etching, lithography and other fabrication techniques. Using these technologies extremely small feature sizes could be produced. Optical lithography, for example, produces features as small as 0.2 µm and X-ray lithography can be used to produce even smaller features [1].

There is an increasing trend towards product miniaturization with the rapid development of microengineering technologies. The development of new microdevices is highly dependent on manufacturing systems that can reliably and economically produce microparts in large quantities. In this context, microinjection moulding of polymer materials is one of the key technologies for serial micromanufacture [2].

Microinjection moulding of thermoplastics is one of the most promising fabrication techniques for non-electronic microdevices. The production costs of moulded microparts are hardly affected by the complexity of the design. Once the mould is made, thousands of parts can be moulded with little additional costs. In most cases the cost of the raw material is negligibly low, because only small material quantities are required for microcomponents. Therefore, parts fabricated by micromoulding, even from high-tech materials, are suitable for applications requiring low-cost and disposable components [3]. Thus the market is continuously demanding technologies for manufacturing large numbers of products at a reasonable price. These two requirements are met by the use of replication technologies, mainly microinjection moulding and micro hot-embossing. There is an agreement on two aspects of the microtechnologies [4]:

- Mass production of microparts must be based on replication technologies.
- Quality and performance of a replicated micropart depend mainly on the quality and performance of the corresponding microtool.

In context of the mould industry, the term micromanufacturing refers to the generation of high precision three-dimensional (3D) components with dimensions ranging from tens of micrometers to some millimetres. Nevertheless, some of the micromachining processes lack the capability to produce complex 3D parts with high aspect ratios.

Some of the best suited processes to create these parts, are for example laser beam machining, mechanical micromachining, electrochemical machining, electro-beam machining, focused ion beam machining and micro electro discharge machining.

Micromanufacturing Processes

The micromanufacturing technologies are a high added value key-element, to a large number of industrial sectors. Besides the creation of 3D microparts with a high aspect ratio, the achievable accuracy and the possibility to produce microdetails are a challenge in micromachining. Frequently many factors interact and the arrangement of these factors determines the capabilities of a technique. The more common techniques used by the micromouldmaking industry include laser beam machining, micromilling and microEDM, which have advantages and disadvantages taht lead to their combined use in the manufacturing of the microtools.

Micromilling

Milling plays a key role in the production of microstructured cavity inserts. In comparison to other manufacturing techniques, such as electro-erosion, laser processing or semiconductor technologies, milling has advantages for low volume production:

- Able to work with hardened tool steels;
- Flexible manufacture of complex geometries;
- Use of existing CAD/CAM infrastructure;
- Comparatively small capital investment.

Micromilling still a rather young process in the micromachining domain is one of the techniques currently associated to microinjection moulding and hot embossing which imply the machining of thin features [5]. In general, micromilling has requirements exceeding those of conventional machining:

- Very high spindle speeds to achieve adequate cutting speeds for the smallest milling cutters.
- Unbalance (short cutting force)
- Very small tools and parts that are difficult to fix.
- Part size and features limited by the smallest diameter of the tools available (currently 40 µm).
- Higher positioning resolution is required.

Laser Beam Machining (LBM)

In laser beam machining (LBM), the source of energy is a laser, which focuses high density light energy on the surface of the workpiece. The maximum depth where absorption occurs is the penetration depth and leads to the conduction of the heat to the material [6]. This mechanism is used in several technologies: laser drilling, laser cutting, engraving and, more recently, 3D-laser machining. The advantages of laser beam technologies over other processing technologies are:

- Easy convertion to automatic operation
- No processing forces
- No tool wear
- High processing speed combined with excellent reproducibility
- Capable to process very hard, brittle and soft materials
- Easy integration with other complementary manufacturing technologies

However, LBM exhibits some disadvantages, such as the formation of a heat affected zone (HAZ), pooor surface roughness, and low aspect ratio.

MicroEDM (µEDM)

Electrical discharge machining is often used for machining complex work piece geometries in tools for injection moulding. Low surface roughness and filigree structures in microtools are obtained with very small discharge energies this making it necessary additional process parameters that make µEDM different from conventional EDM. In µEDM the energy of the discharge must be minimized and the frequency of the discharges increased [7]. µEDM is very appropriate with conductive materials which cannot be machined by micromilling, e.g. hard alloyed, chemically highly resistant 1.4539 steel for chemical microreactors. Furthermore, as micro milling is limited to rather small aspect ratio of the geometries in the work pieces, µEDM became a domain of deep concave geometries.
µEDM is advantageous due to:

- Machinability being independent of raw material hardness
- Versatile forms can be machined
- No mechanical forces involved (available to erode ribs with high aspect ratio)

The disadvantages result from only conductive or semi conductive materials being machined, limited surface roughness possible, existence of a heat affected layer and the wear of the electrode.

Experimental

Test parts

Two test parts were designed to evaluate a) the manufacturing issues for a microinjection moulding cavity such as the technology adopted and the obtained surface finishing; and b) the polymer behaviour on filling features such as thin walls and high aspect-ratio ribs. From the manufacturing point of view, the cavities for the ribs represent a challenge even considering the small aspect ratio of the features. The surface finishing of the side walls should enable a smooth ejection process, requiring the selection of appropriate strategies for manufacturing.

The first test part, featuring two ribs, was manufactured using micromilling and µEDM, and is represented in Figure 1. The second test part (*Figure 2*) combines the use of LBM for the manufacture of the rib with a cylindrical protrusion with a through hole manufactured by micromilling.

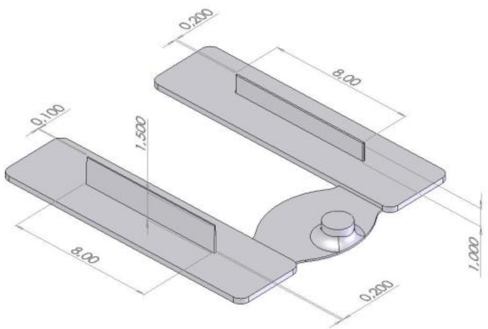

Figure 1 – Geometry of the first test part

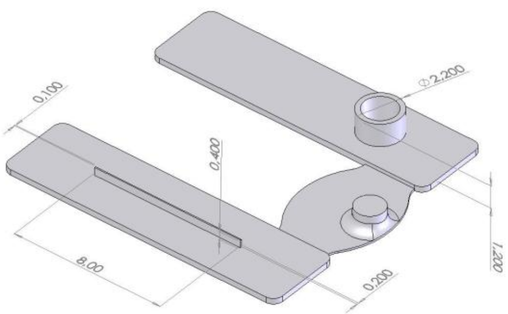

Figure 2 – Geometry of the second test part

Materials

The moulding blocks were manufactured with stainless steel DIN X42Cr13 after quenching and tempering to a hardness of 490 ±9 (HV0.01). This 13% chromium stainless steel is used in moulds for plastics where high hardness upon heat treatment and good polishing are required. The moulding blocks are depicted on Figure 3.

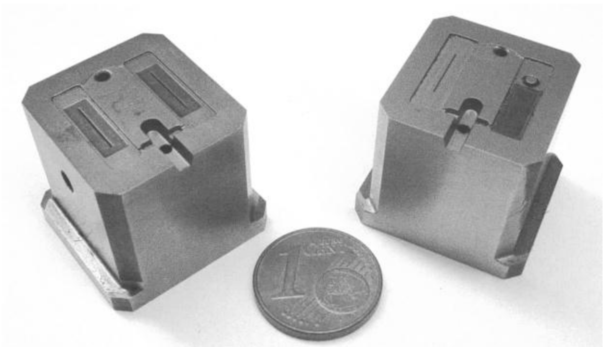
Figure 3 – Moulding blocks

The injection tests were carried with polyoxymethylene (POM), Hostaform C27021 from Ticona-Europe (Kelsterbach, Germany). This grade is very easy flow injection moulding with MFR of 24 cm^3/10 min (190ºC, 2.16 kg) and is commonly used in microinjection moulding [3].

Manufacturing equipment

The micromilling operations were made with a FIDIA HS644 High Speed Micro Machining Center (Torino, Italy) with a spindle speed of 36.000min^{-1}. The parameters used for manufacturing are listed in Table 1.

Table 1 – Micromilling parameters

Parameter	*Units*	*Values*
Cutting Speed (V_c)	$m.min^{-1}$	68
Spindle Speed (n)	min^{-1}	36.000
Feed per tooth (f_z)	μm	4
Width of cut (a_e)	μm	4

For the laser beam machining process, a Deckel-Maho DML 40 SI equipment (Bielefeld, Germany) with 100 W Nd:YAG-type pulsed laser with wavelength of 1064 nm was used. The operating parameters used for manufacturing are listed in Table 2.

Table 2 – Laser beam machining parameters

Parameter	*Units*	*Values*
Pulse frequency	kHz	30
Cutting depth	μm	2
Hatching	μm	10

μEDM was performed with an AgieCharmilles Hyperspark (Geneve, Switzerland). The operating parameters are described in Table 3.

Table 3 – μEDM parameters

Parameter	*Units*	*Values*
Current Intensity	A	0,8
Voltage	V	120
Pulse time	μs	7,5 - 32
Pause time	μs	2,4

Microinjection moulding cell

The microinjection cell consists of a Boy 12A injection moulding machine, a mould temperature regulator and an external control unit for the cartridge heaters used in the temperature control system of the mould (Figure 4).

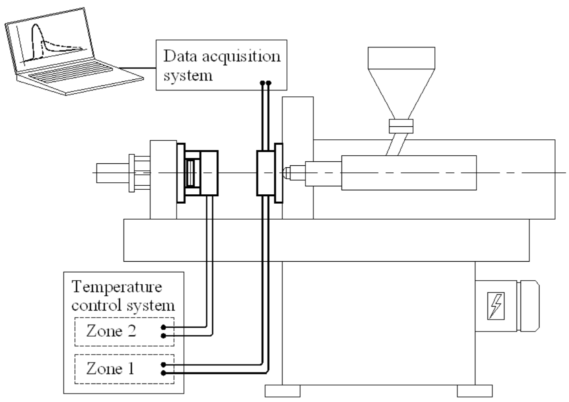

Figure 4 – Layout of the microinjection cell

The injection moulding machine Boy 12A (Dr Boy GmbH, Germany) with Ø14 mm injection screw combines technical characteristics for microinjection and affordability [8, 9]. It is adequate for microinjection, for being able to precisely meter with injection volume as small as 0,1 cm^3 at flow rates up to 15,6 cm^3.s^{-1}. The maximum injection pressure is 240 MPa.

The processing conditions summarized in Table 4.

Table 4 – Processing conditions

Parameter	***Units***	***Values***
Melt temperature	ºC	200
Mould temperature	ºC	95
Injection speed	mm.s^{-1}	100
Injection pressure	MPa	100
Holding pressure	MPa	80
Holding time	s	2

Filling simulation

Numerical simulations were performed with the software Moldex3D R9.1 (CoreTech, Taiwan). This software release incorporates the latest refinements concerning heat transfer, which is one of the most important factors determining the process behaviour at the microscale. Filling simulations were performed with the same processing parameters used in microinjection. A hybrid solid mesh was used, optimizing the number of elements and calculation time. At least, four elements are present on the part thickness improving simulation reliability, required to model polymer flow on thin walls, such as the ribs created on the test parts. Figure 5 shows an internal detail of the hybrid mesh.

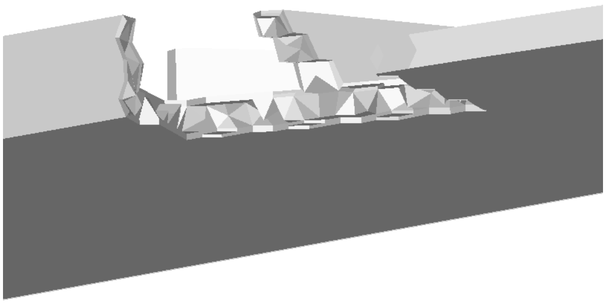

Figure 5 – Mesh detail on the simulation model

Results and discussion

Three evaluations were performed, concerning a) cavities characterization, before and after being used for the microinjection process, b) replication and shrinkage analysis of the plastic parts; and c) comparison of experimental results with numerical simulations concerning shrinkage and warpage behaviour of the plastic microparts.

Cavity characterization

The characterization of the textured surfaces was done by tactile roughness profilometry using a Perthometer M1 roughness tester (Mahr, Germany) with resolution of 10 nm. The measurements followed the ISO 4287 standard. The parameter used to evaluate the surface roughness was the arithmetic mean roughness (Ra) as relative heights in microtopographies are more representative, especially when measuring flat surfaces. The topography evaluation of the surfaces was done by Scanning Electron Microscopy using JEOL JSM-5310 equipment (JEOL Ltd, Japan).

The roughness evaluation performed on the moulding blocks before and after the microinjection procedure showed that wear due to polymer flow had a significant effect on the surface. This may be considered as an unexpected result, considering that tool steel has been used for this application. The results of both roughness evaluations are listed on Table 5.

Table 5 – Roughness Ra data

Surface machining	***Before***	***After***
Micromilling	0,221 µm	0,022 µm
LBM	0,588 µm	0,485 µm
µEDM	0,075 µm	0,023 µm

This effect is particularly noticeable on the micromilling and LBM surfaces where a significant decrease on surface roughness occurs. The slight improvement on the LBM surface is no surprise since the process causes the re-solidification of debris over the processed area. Such debris may have been partially dragged by polymer flow, an effect that could be enhanced by the increase of shear rate up to critical values, causing a shift on the flow regime to a plug-flow [10]. There is no enough evidence to support the existence of high melt speeds on the cavity. However, the dragging of moulding block particles enables that suspicion. The moulding surfaces, prior to the microinjection procedure are shown on the Figures 6 to 8, respectively, for micromilling, LBM and µEDM.

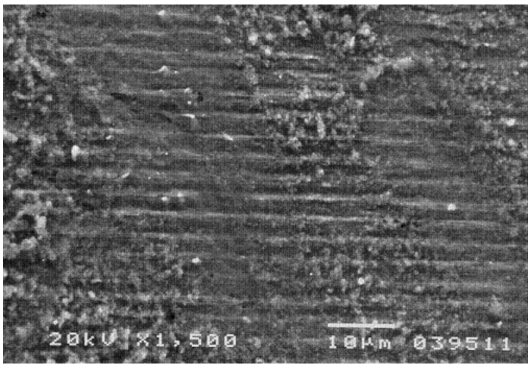

Figure 6 – SEM micrograph of the micromilled surface

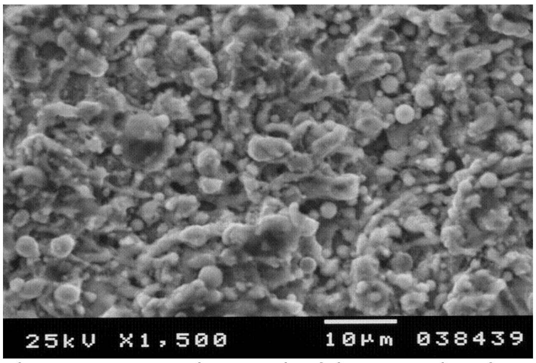

Figure 7 – SEM micrograph of the LBMed surface

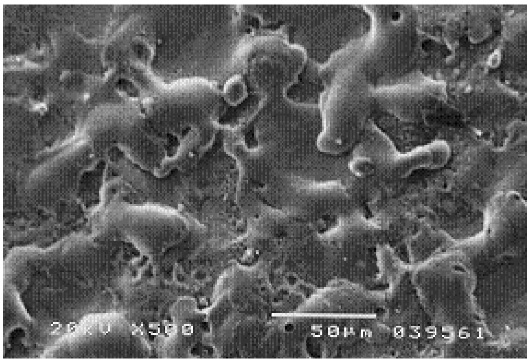
Figure 8 – SEM micrograph of the µEDMed surface

Part analysis

The plastic parts produced were analysed to determine the quality of replication on to cavity surface. Therefore, measurements were carried out to determine shrinkage at this level of dimensions and visual inspection was performed to detect any surface defect or anomalies. The shrinkage data of the two test parts are listed in Table 6.

Table 6 – Shrinkage analysis

Shrinkage		***Base***	***Rib/Boss***
First test part	**Along X axis**	3,15%	2,41%
	Along Y axis	3,04%	20,14%
	Along Z axis	2,06%	2,83%
Second test part	**Along X axis**	2,91%	3,35%
	Along Y axis	3,14%	19,57%
	Along Z axis	1,65%	5,42%

Although the X, Y and Z axes data on the base of the parts are quite similar, the shrinkage values in the Y-direction is highly affected by the measurements on the base of the rib, an area that shows the highest values of shrinkage. This effect is expectable considering that the material at the base of the rib is the last to solidify. Despite the fact that there is virtually no core on thin walls, a significant shrinkage value still occurs at that location.

Concerning defects on the plastic parts, a frequent anomaly is the warpage of the part. Two additional causes contribute to that problem: the location of the ejector pins on the extremities of the part and the friction associated to the depth of the ribs. As expected, the higher is the aspect-ratio, the higher is the probability of occurring problems on the ejection phase.

Filling simulation versus experimental

The comparison between numerical simulation and actual micromoulding considered the shrinkage referred to in the previous topic and the warpage of the mouldings. Furthermore, considering the accuracy of the simulations, it is important to access the effectiveness of the simulation by using the same processing parameters as used on the microinjection procedure. For that purpose, a simulation model of the first test part was used to perform such comparison. Concerning the filling, the part was predicted to correctly fully fill as shown in Figure 9.

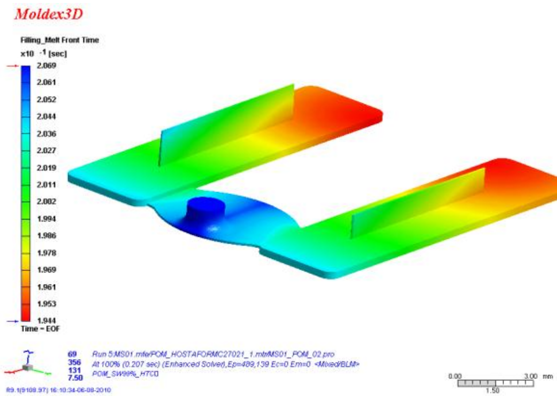

Figure 9 – Filling melt front time

Regarding shrinkage, the Moldex3D values were realistic. Shrinkage slightly below 3% was observed for this test part as referred to in the previous topic. The simulation predicted a maximum volumetric shrinkage value close to 9%, as illustrated on Figure 10. Considering that the linear shrinkage is approximately one third of the volumetric shrinkage, it is possible to conclude that the numerical simulation was quite accurate.

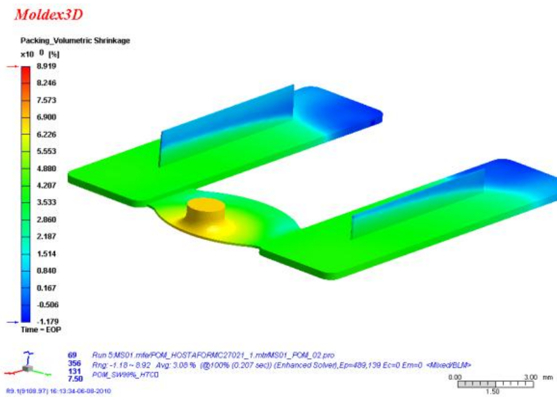

Figure 10 – Volumetric shrinkage upon packing

However, the moulded parts exhibited high shrinkage values at the base of the ribs while Moldex 3D® predicts values ranging from 3,5% to 4,8% in that area.

In which concerns to the warpage of the plastics parts, the numerical simulation also proved to be reliable, the warpage prediction was coherent with the experiments and to what is normally expected for this type of geometry. The results of the warpage simulation carried out for the first test part are shown in Figure 11.

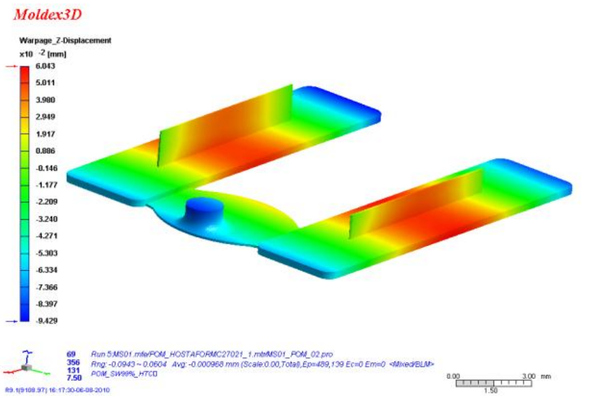

Figure 11 – Warpage on the Z direction

The moulded parts exhibited a higher displacement at the middle in the Z direction than the correspondent simulation result. Moldex 3D® predicts a maximum deflection of 155 µm while the parts show deflection values close to 500 µm at the middle. Due to the additional causes described before it is not possible to compare directly the warpage magnitude between the numerical solution and the experiment.

Conclusions

For martensitic stainless steels, as X42Cr13, the surface roughness deteriorates with increasing laser intensity. The adjustment of other laser parameters carried out a significant improvement in surface finishing quality. The lowest roughness for the X42Cr13 steel is reached with hatching and overlapping of 10 µm using a 30 µm spot diameter. Although it cannot yet be fully proved, it is possible that plug-flow is the cause for the decrease of surface roughness on machined surfaces.
Despite the fact that numerical simulation tools are still not fully adjusted to the rheological description of the flow at the microscale, Moldex3D predicted with reasonable accuracy the filling process, the shrinkage and the warpage of micromouldings.

Acknowledgements

The authors acknowledge Centimfe for metrology and roughness evaluations. This research work was supported by the Portuguese Foundation for the Science and Technology under the grant SFRH/BD/36982/2007 to J. C. Vasco.

Bibliography

[1] Malek, C.K. and V. Saile, *Applications of LIGA technology to precision manufacturing of high-aspect-ratio micro-components and -systems: a review.* Microelectronics Journal, 2004. **35**: p. 131-143.
[2] Sha, B., et al., *Study of Factors Affecting Aspect Ratios Achievable in Micro-injection Moulding* in *4M2005 Conf. on Multi-material Micro Manufacture*. 2005, Elsevier: Karlsrhue. p. 107-110.
[3] Heckele, M. and W.K. Schomburg, *Review on micro molding of thermoplastic polymers.* Journal of Micromechanics and Microengineering, 2004. **14**(3): p. R1-R14.
[4] Uriarte, L., et al., *Comparison between microfabrication technologies for metal tooling.* Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 2006. **220**(11): p. 1665-1676.
[5] Popov, K., et al., *Micromilling: material microstructure effects.* Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 2006. **220**(11): p. 1807-1813.
[6] Jackson, M., *Micro and Nanomanufacturing*, ed. Springer. 2006.
[7] Descoudres, A., *Characterization of electrical discharge machining plasmas*. 2006, École Polytecnique Fédérale de Lausanne: Lausanne. p. 125.
[8] Piotter, V., et al., *Injection molding and related techniques for fabrication of microstructures.* Microsystem Technologies, 1997. **3**(3): p. 129-133.
[9] Song, M.C., et al., *Research on effects of injection process parameters on the molding process for ultra-thin wall plastic parts.* Journal of Materials Processing Technology, 2007. **187**: p. 668-671.
[10] Vasco, J.C., J.M. Maia, and A.S. Pouzada, *Thermo-rheological behaviour of polymer melts in microinjection moulding.* Journal of Micromechanics and Microengineering, 2009. **19**(10).