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Effects of micro-injection moulding process parameters on accuracy and precision of thermoplastic elastomer micro rings

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ABSTRACT

Micro-injection moulding (μIM) represents the only technology currently capable of enabling the mass production of polymer micro-components. Although this process is mainly utilized to process rigid thermoplastics, the development of new fields of application asks for the extension of the technology potential to novel types of polymeric materials such as soft thermoplastic elastomers (TPEs). In this work, the authors studied the μIM technology of TPE micro suspension rings for sensor applications. An initial benchmark study, based on microscopy inspections and weld line depth measurements, allowed identifying suitable process parameters settings. Then, the effects of the process parameters on the dimensional variation of the outer and inner diameter of the produced micro rings were quantified. A focus variation microscope and an optical coordinate measuring machine were employed for the measurements of parts and mould cavities respectively. The results of this study showed that the outer ring diameter was mostly affected by mould temperature and holding pressure, while the inner one depended mainly on mould and melt temperature. It was also found that the investigated process parameters had an opposite effect on the outer and inner diameter variations, posing great challenges in the achievement of the part geometry specified in the design.

1. Introduction

Over the last decade, the need of miniaturized, complex-shaped components has drastically increased in several fields such as medicine, biotechnology, automotive, avionics, communication, etc. [1]. In order to meet this fast growing request of both precision and productivity, the manufacturing community reacted either by designing brand new micro-manufacturing processes or by developing well established ones and adapting them to the new challenging demands [2].

Within this scenario, micro-injection moulding (μIM) represents the miniaturized counterpart of the conventional injection moulding technology. The peculiarity of this process lies in the fact that it successfully combines the cost-effective production of complex and net-shaped plastic parts with the capability of accurately and precisely manufacturing micro components [3]. In order for a product to be considered in the μIM domain, it has to belong to one of the following categories [4,5]:

- Parts with outer dimensions in the millimetre range or larger, but locally featuring structures in the micrometre range. This class is typical of microfluidic devices.
- Parts with larger outer dimensions but dimensional tolerances in the micrometre range.
- Small parts with outer dimensions in the micrometre scale and mass in the milligram order.

Being the miniaturized adaption of conventional injection moulding, μIM presents the same overall process cycle: the plastic granules are melted, metered and then injected into the mould cavity in the form of a viscoelastic polymer flow. After packing and cooling, the moulded product is ejected. However, even though the physics behind the two technologies is the same, new challenges and fundamental differences arise when downscaling the process [6]. In fact, dedicated micro machines, micro tooling processes, different modelling approaches and new measuring solutions are all needed to carry out a repeatable and controllable injection moulding process in the micro-scale [7–9]. In order to face all these challenges, extensive research has been carried out in the last decade. Nowadays, the μIM process is fairly developed in the field of rigid thermoplastics. These materials, being low cost, relatively easy to process and stiff, cover a preponderant part of the polymer materials processed by μIM. In fact, the current main application of μIM is represented by the microfluidic devices industry, which relies on the manufacturing of rigid and micro/nano-structured 2.5D parts [10]. Table 1 reports examples of the most commonly used thermoplastic polymers in μIM and their applications.

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Table 1
Rigid thermoplastics used in µIM components.

Materials	Micro-applications	Reference
Polyoxymethylene (POM)	Micro filter, Dog-bone tensile sample	[11,12]
Polycarbonate (PC)	Ultra-high aspect ratio nano pillars, Optical part	[13,14]
Liquid Crystal Polymer (LCP)	Toggle for hearing aids	[15,16]
Poly(methyl methacrylate) (PMMA)	Nano-structured part, Microfluidic platform	[17,18]
Polypropylene (PP)	Micro-structured part, Microfluidic distributor	[19,20]
Acrylonitrile Butadiene Styrene (ABS)	Micro pillars, Microfluidic part	[21,22]
Polystyrene (PS)	Bio-MEMS component, Micro-structured part	[23,24]
Cyclic Olefin Copolymer (COC)	Micro-featured part, Microfluidic device	[25,26]

The research on µIM applied to other classes of polymeric materials is very limited. New research has to be carried out to extend the technology potential to new materials in order to broaden its fields of application. With this aim, this present paper focuses on thermoplastic elastomers (TPEs).

Thermoplastic elastomers are polymeric materials that combine the melt processability typical of thermoplastics and the elastomeric behaviour of vulcanized rubbers [27]. The fundamental difference between rigid thermoplastics and TPEs regards their mechanical properties: the first are rigid and stiff, while the second are soft and flexible. Therefore, TPEs exhibit the distinctive characteristics of thermoset rubbers and are, at the same time, easy to process as thermoplastic polymers. The explanation of the ambivalent behaviour of thermoplastic elastomers lies in their structure. Most TPEs are phase-separated systems: one phase is hard and crystalline at room temperature, while the other is an elastomer [27]. The hard phase confers the strength and acts as physical cross-link, whereas the elastomeric one interconnects the rigid phases providing flexibility and elasticity to the system. The transition temperatures of TPEs, and thus their process window, are determined by the characteristics of both the phases. Below the glass transition temperature of the elastomeric phase, the TPE is brittle and stiff. Above this temperature, the material is soft and elastic, similarly to rubber. Finally, when the temperature is higher than the melting temperature or glass transition temperature of the hard phase, the TPE turns into a viscous fluid and becomes processable by means of injection moulding. TPEs are usually preferred to thermoset rubbers because of their simpler manufacturing process and shorter fabrication times [27]. The possible re-moulding also represents an important advantage. Finally, the exceptional repeatability of the injection moulding process allows manufacturing TPE components with tighter tolerances compared to conventional thermosets rubbers. Thus, thermoplastic elastomers represent the best solution for manufacturing precision and micro parts featuring softness and flexibility.

Although the injection moulding process of TPEs is well established and widespread for macro scaled components [28], very few studies report about their use in combination with µIM. Alabran et al. [29] studied the effects of process conditions and tooling on the replication of nano-scale features (patterns size ranging from 100 nm to 1500 nm) using two different thermoplastic polyurethanes and varying only the mould temperature. Attia et al. [30] proposed and validated the micro-overmoulding process of TPE for the manufacture of a 3D microfluidic system. The rigid substrate was made of poly(methyl methacrylate) (PMMA) while the TPE was a styrene-ethylene-butylene-styrene (SEBS) copolymer. The assembled device was tested against leakage, but no study regarding the process parameters effect on the product dimensional accuracy was performed.

The present paper studies the µIM technology of TPE miniaturized suspension rings employed in sensor applications. An initial benchmark study based on scanning electron microscopy and weld line depth measurements allowed identifying a suitable process window. Then, a comprehensive experimental study based on design of experiments (DOE) was carried out in order to evaluate the effects of the moulding process on the part functional geometries. With the aim of evaluating the actual replication capability of the process, the mould cavities were also measured and used as reference for the investigation.

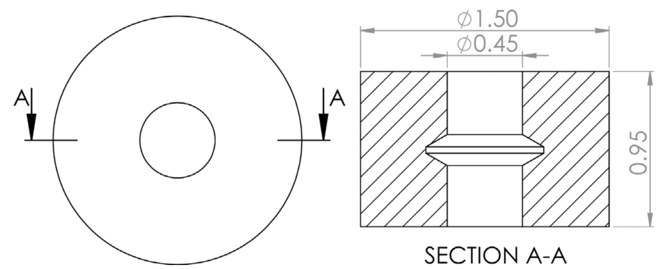

Fig. 1. Geometry and nominal dimensions in mm of the micro suspension ring.

2. Materials and methods

2.1. Case study

The micro component under investigation was a TPE micro suspension ring utilized as a component of a micro sensor. Since this application demanded both high dimensional accuracy and dampening properties, µIM of TPE represented the only solution allowing meeting the functional requirements. Fig. 1 shows the shape and main dimensional features of the investigated suspension micro ring.

The internal geometry of the ring presents a conical structure, making the component three-dimensional. Being the nominal part mass equal to 2.2 mg and the dimensional tolerances ± 10 µm on both internal and external diameters, the component falls in the category of micro products according to the aforementioned definitions.

The present work focuses on the outer dimeter (OD) and inner diameter (ID) of the rings, since they represent the most significant geometries with respect to the part functionality.

2.2. Mould design

A three-plate mould with replaceable insert was developed and used in the experiments. The main advantage of this type of mould is that the separation of the part from the feed system was achieved automatically by means of the movement of the middle plate. The use of such a strategy is relatively common in conventional injection moulding, but few examples of three-plate moulds utilized for µIM purposes exist [30–32]. Both the mould plates and the insert were made from tool steel. Four cavities were machined on the insert and the internal geometry of the micro rings was created by means of micro pins protruding from the fixed ejection plate. Both the cavities and the micro pins were machined using micro-electro-discharge-machining (µEDM). Taking into account the nominal shrinkage of the TPE material and the target part dimensions, the four cavities were designed with diameter 1.550 mm while the pins with diameter 0.480 mm. The feed system consisted in a cylindrical sprue connected to the cavities through four runners and pin gates. Fig. 2a and b illustrate the design of the three-plate mould. Fig. 2c shows how the feed system was located in the mould frame.

After the end of each moulding cycle, the four micro rings were ejected by means of ejector tubes around the pin, thus ensuring a full automatic procedure. It is worth noting that such an ejection system relied on the softness and elasticity of TPE. In fact, the undercut introduced by the internal rings geometry (see Fig. 1) would have made the ejection impossible if a rigid thermoplastic material was used.