Study of process parameters effect on the filling phase of micro-injection moulding using weld lines as flow markers

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Abstract Micro-injection moulding (micro-moulding) is a process which enables the mass production of polymer micro-products. In order to produce high-quality injection moulded micro-parts, a crucial aspect to be fully understood and optimised is the filling of the cavity by the molten polymer. As a result, the relationships between the filling pattern and the different process parameter settings have to be established. In this paper, a novel approach based on the use of weld lines as flow markers to trace the development of the flow front during the filling is proposed. The effects on the filling stage of process parameters such as temperature of the melt, temperature of the mould, injection speed and packing pressure have been investigated. An optical coordinate measuring machine has been employed for the investigation. The micro-cavity, which presents micro-features ranging from 600 \( \mu \text{m} \) down to 150 \( \mu \text{m} \), has been manufactured by micro-electrodischarge machining. A commercially available polystyrene grade polymer has been moulded using a high-speed injection moulding machine. The design of experiment technique was employed to determine the effect of the process parameters on the filling phase of the micro-cavity. In addition, extensive measuring uncertainty analysis was performed to validate the experimental plan. Results show that the temperature of the mould and the injection speed are the most influencing process parameters during the injection moulding of a micro-component.

Keywords Micro-injection moulding · Weld lines · Design of experiments · Process analysis · Uncertainty

1 Introduction

In the last few years, the market of micro-products has been constantly increasing. Micro-engineering is a key sector for the development of new technologies for micro-applications. The use of micro-systems covers very large and differentiated fields. Some examples include information technology components (reading caps for hard disc, ink jet printers nozzles, etc.), medical and biomedical devices (pacemaker, sensors, micro-fluidic systems for analysis of bio-fluids etc.), high technology products (palm-sized high-definition displays, mobile phones etc.) and motion sensors for the automotive industry, micro-components for implant devices as hearing aid systems (micro-connectors, micro-switches etc.).

For the mass fabrication of micro-products, micro-injection moulding (\( \mu \text{IM} \)) represents one of the most important manufacturing processes because it matches the capabilities of a low-cost process and the requirements of micro-products, as dimensions in the sub-millimetre range and low tolerances (in the order of few micrometres down to sub-micrometre range). Micro-injection moulded components can be divided in the following three classes, depending on their characteristic features [18]:

- Micro-injection moulded parts that weigh from a few milligrams to a fraction of a gram and have dimensions on the micrometre scale (e.g. micro-gear, micro-operating pins)
• Injection moulded parts of conventional size which have micro-structured regions or micro-features (e.g., compact discs with data pits, optical lenses with micro-surface features, information carriers in very small devices such as sensor discs)
• Micro-precision parts that can have any dimensions but have tolerances in the micro-scale (e.g., connectors for optical fibre technology)

The miniaturisation of components leads to new problems in micro-forming processes and more attention is needed in all production steps [5]. The know-how of conventional technology cannot be transferred easily to micro-technology since the material behaviour (e.g., its rheology) changes in the micro-scale [22].

The reliable manufacture of polymer-based micro-components is directly connected to the capability of controlling the micro-injection moulding process. A crucial step during the process is the filling of the cavity. It is important to understand the influence of the process parameters on the filling of a micro-cavity for the optimisation of the process and to obtain completely filled micro-parts complying with the specifications. Therefore, further experimental activities are needed in order to fully understand the process dynamics during the micro-moulding process.

Characterisation of the filling phase during micro-injection moulding is a challenging task, mainly due to the dimensions of the cavity (typically in the sub-millimetre range and even down to a few micrometres) and the filling time of the cavity (in the order of a few tens of milliseconds). In order to overcome those challenges, an alternative new method, based on the measurement of the weld lines path on the surface of a micro-part, is proposed and investigated. The position of weld lines was affected by the processing conditions and worked as flow markers of the melt-flow development during the filling of the cavity. The influence of four process parameters (melt and mould temperatures, injection speed and packing pressure) was analysed and will be presented.

The paper is structured as follows: Section 2 presents the state-of-the-art and flow pattern analysis methods applied to micro-injection moulding. In Section 3, the method based on the use of weld lines as flow marker is introduced. In Sections 4 and 5, the experiments and the results from the application of the new method are presented. In Sections 6 and 7, the filling analysis results are presented and discussed, respectively. Finally, conclusions and recommendations for future research work are included in Section 8.

2 Filling pattern tests

Different approaches can be employed for the analysis of the filling stage of the micro-injection moulding process. In the following sections, a review of results obtained during recent research works is reported. In particular, three methodologies can be applied in order to characterise filling patterns:

• Short shots, where the filling pattern is obtained by means of partially filled mouldings of increasing volume (see Section 2.1)
• Flow visualisation, used to show the progress of the melt front in the cavity during the injection phase (see Section 2.2).
• Length flow test, used to evaluate the filling capacity of the moulding system in terms of achievable flow length and aspect ratio (see Section 2.3).

2.1 Short shots method

In conventional injection moulding (i.e., in the macro-dimensional range), a common approach used to study the development of the melt flow inside the cavity is the short shots analysis. It consists on the injection of fractions of the molten polymer volume necessary to completely fill the cavity. The application of the short shots method to micro-injection moulded parts has been shown to be possible when using a micro-injection moulding machine provided with an injection plunger [19]. One of the main conditions for the applicability of such method is that the resolution of the metering process (i.e., the smallest shot volume that can be injected in a controlled manner) has to be smaller than a fraction of the part which is significant to give information about intermediate stages of the filling. This condition can be fulfilled by micro-injection moulding machines having an injection unit with a plunger. On the other hand, small injection moulding machines with the conventional plastication unit with reciprocating screw cannot provide controlled short shots in the order of fraction of 1 mm³ (i.e., the typical volume of polymer micro-parts and/or micro-features). Furthermore, in conventional machines, the acceleration of the screw may not be high enough to provide the required injection speed in the very short time needed to produce micro-short shots. As a result, despite the fact that it is actually possible to injection mould micro-parts with conventional injection moulding machines (especially if electrically driven and capable of high injection speed), with such machines, it is not possible to produce reliable micro-short shots. The repeatability of process conditions in terms of actual speed and injection pressure at the very beginning of the screw movement is lower than when it has reached a steady-state injection movement. Moreover, the produced incomplete micro-parts present free surfaces with a deformation due to stress relaxation and thermal contraction. This causes an approximation on the dimensional accuracy of the determination