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Impact of deep cores surface topography generated by micro milling on the demolding force in micro injection molding

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ABSTRACT

In micro injection molding the quality of 3D complex parts is influenced by the efficiency of the ejection phase. During demolding, the forces taking place at the component-tool interface, due to adhesion and friction, need to be overcome preserving the integrity of the part. This issue is severe in the case of molds characterized by the presence of several deep cores, which are used to manufacture interconnecting through holes in multi-layer microfluidic devices. In this work, the impact of the micro milling cutting strategy on the demolding forces was investigated, using a critical cavity geometry, specifically designed to this purpose. The relation between mold micro manufacturing and the micro injection molding process was studied with the aim of optimizing the demolding phase. The topographies of micro-milled mold surfaces and the molded parts were characterized and different roughness profile parameters were taken in consideration. The results of in-line force acquisitions indicated that the effects of the micro milling strategy on the demolding force is markedly higher than those of micro injection molding process variables. Moreover, the experimental analysis indicated that a combination of worst surface finishing and low viscosity of the molding polymer can result in higher interface interlocking and thus in critical stresses applied to the part during the demolding phase.

1. Introduction

Lab-on-a-chip are devices integrating several complex laboratory functions on a single chip to achieve automated and high-throughput analysis. These devices find their main application in the biomedical industry, e.g. drug testing and DNA analysis, and their functionalities are allowed by the presence of several micro features on their surfaces (Gornik, 2004). The research in this field aims at developing new devices allowing more complex analysis in a simple and economic way. Consequently, developing effective manufacturing process chains supporting their mass production becomes an issue (Attia et al., 2009). Indeed, Lucchetta et al. (2014) investigated the capabilities of the micro injection molding process in replication a micro-structured surface, highlighting the inherent limitations of the process.

In this context, micro injection molding (μIM) is a key enabling technology with the potential to mass-produce 3D complex parts at a low cost. However, as reported by Giboz et al. (2007), the demand for increasing complexity, and the trend toward miniaturization, poses several technological issues. In particular, the filling and the ejection phases are critical steps in determining the efficiency of the process.

Lucchetta et al. (2016) observed that injection molding of micro parts is a challenging task because of the higher raise of cavity pressure that can prevent the complete replication of the mold geometry. On the other hand, Heckele and Schomburg (2003) suggested that part possessing dimensions or tolerances in the micrometric range make the ejection phase particularly critical. Thus, the understanding of process constraints for the production route is essential at both the design and manufacturing stages.

In μIM, the demolding phase is carried out through the application of ejection forces in some designed locations of the part, as indicated by Araújo and Pouzada (2002). Marson et al. (2011)

Abbreviations: μIM, micro injection molding; DoE, design of experiments; P_h, packing pressure; t_c, cooling time; V_{inj}, injection speed; F_{peak}, peak of the demolding force curve; F_{area}, area subtended to the demolding force curve; COC, cyclic olefin copolymer; PS, polystyrene.

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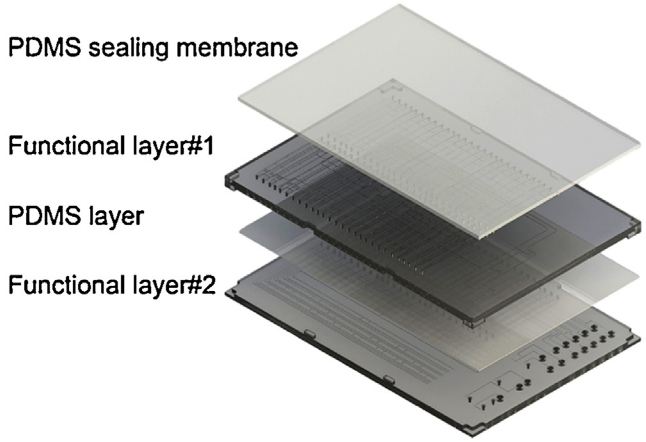

Fig. 1. Example of multi-layer chip: 2 functional polymer layers – 2 PDMS sealing membranes.

observed that ejector pins can apply high local stresses to the part, causing possible distortion, stress marks and fractures.

Griffiths et al. (2010a) described that ejector pins should overcome the local friction at the part-tool interface without damaging the final parts. Current solutions, based on intuition and experience, are not effective for complex micro parts and a unified systematic approach for solving demolding problems does not currently exist (Delaney et al., 2012). Thus, the development of systematic approaches to mold design, as well as process monitoring and optimization are required to improve the quality of micro-molded parts.

These issues are particularly critical in the case of multi-layer microfluidic devices, where the mold cavity has several features that counteract the shrinkage of the polymer melt (Marson et al., 2011). Indeed, the interconnections between the different layers are ensured by several arrays of through holes (Fig. 1) that are realized by a series of deep cores tools in the mold. Typical multi-layer microfluidic devices involve critical design conditions, which lead to manufacturing issues. In particular, the presence of small through holes is a common design solution that allows the exchange of small volumes of fluids between the device layers through small pipes. In order to reduce the device dimension, whilst maintain high complexity/functionality, the holes are commonly arranged in tight arrays. The combination of these design conditions makes μIM, and especially its ejection phase, particularly critical. In fact, Delaney and Kennedy (2010) described the development of demolding stresses during the μIM process, indicating how the normal force resulting from the polymer shrinkage affects the tangential force required during demolding and thus the efficiency of the demolding phase. Hence, the successful separation of the replicated part from the mold requires to develop a reliable micro manufacturing process chain (Heckele and Schomburg, 2003).

The shrinking of the polymer part, constrained by the tool during the μIM process, causes an increase of the thermally-induced stress in the moldings, as described by Menges et al. (2001). The retaining forces that take place at the part-tool interface need to be overcome by a tangential force, generating a relative motion between the part and the tool. The successful manufacturing of plastic micro parts, characterized by high precision and good tolerances, requires to consider how the demolding force can be reduced (Marson et al., 2011). Hence, the factors influencing the demolding phase have to be understood and analyzed to avoid any detrimental effects on molded parts (Griffiths et al., 2010b).

The polymer shrinkage in the μIM process can be controlled by appropriately selecting the controllable process parameters (Annicchiarico and Alcock, 2014). In particular, a correlation exists between pressure during filling and packing phases and demolding parameters, as investigated by Griffiths et al. (2015). In their research, they showed that a proper combination of process parameters should be identified to achieve an optimal demolding behavior. Pontes and Pouzada (2006) noted that higher pressures reduce the differential shrinkage in the part, thus the diametric shrinkage and the consequent adhesion of the polymer to mold cores. However, Pontes and Pouzada (2004) reported that when the applied packing pressure was lower a smaller ejection force was observed, because of the larger through-thickness shrinkage that can cause smaller contact pressure at the part-tool interface. Moreover, the ejection forces are influenced by the process thermal boundary conditions. In particular, the temperature of the part in the demolding phase determines the polymer elastic modulus and affects the part-tool interface friction (Pontes and Pouzada, 2004).

Pouzada et al. (2006) described the friction mechanism at the polymer-tool interface, indicating that it is also controlled by the mold temperature, which determines the interlocking between the polymer melt and the mold that is formed during the filling phase. In their work, they evaluated the coefficient of friction using a prototype apparatus showing that, due to replication, it can reach very large values (above 0.9).

Both the pressurized filling of the cavity and the shrinkage taking place during the part cooling, contribute to the surface interlocking, making the topography of the mold surface a fundamental parameter, as described by Ferreira et al. (2004).

Masato et al. (2016) analyzed the filling of a micro-structured surface by μIM, indicating that during the injection phase the polymer melt is driven into the mold cavity, and replicates the mold surface texture. Hence, the plastic part tends to stick over the cores surface after cooling, closely reproducing its surface finish. Therefore, the tribological conditions at the part-mold interface during the ejection phase are not only determined by the shrinkage-induced stresses, but also by the replication of the mold topography and the consequent mechanical interlocking. Moreover, Attia and Alcock (2009) studied the application of μIM processes to the replication of a micro-structured surface and they regarded the packing pressure as the main driving force that compels the polymer into micro cavities. Consequently, this process parameter should be considered as a possible cause of higher part-tool surface interlocking.

The interaction between the part and the tool at the beginning of the ejection phase determines the coefficient of friction between the two surfaces. The polymer part friction during the ejection phase can be interpreted considering a two-term non-interacting model that combines both adhesion and deformation contributions (Kim and Suh, 1991):

- adhesion is a surface effect, which derives from the physical attraction forces between metal atoms and polymer molecules close to the interfacial area (Wu, 1982);
- deformation is a bulk effect governed by the mechanical interlocking intensity between the replicating tool and the part, which produces two different kinds of friction mechanisms: ploughing of solid metal surface asperities over the soft polymer surface (Kim and Suh, 1993) and elastic deformation of polymer surface asperities (Suh et al., 1994).

The forces applied by the ejector pins, have to overcome the initial stiction by deforming the polymer side of the interface.

Micro injection molding tools are mainly produced by machining processes, such as micro milling (Fig. 2), characterized by an inherent surface roughness (Masuzawa, 2000). Parenti et al. (2017) investigated the generation of surface footprint in micro milling,