Journal of Materials Processing Technology 237 (2016) 1–11

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

journal homepage: www.elsevier.com/locate/jmatprotec

Development of a rapid surface temperature variation system and application to micro-injection molding

Felice De Santis*, Roberto Pantani

Department of Industrial Engineering, University of Salerno—Via Giovanni Paolo II, 132, 84084 Fisciano (SA), Italy

ARTICLE INFO

Article history:
Received 23 February 2016
Received in revised form 13 May 2016
Accepted 21 May 2016
Available online 24 May 2016

Keywords:
Micro-injection molding
Rapid heat cycle molding
Thermoplastic materials
Mold design

ABSTRACT

In conventional injection molding, the mold temperature control is obtained by a continuous cooling method, in which a coolant with constant temperature is circulated in the cooling channels to cool the mold and the polymer melt. During the filling stage, this causes an abrupt polymer solidification close to the mold surface, which reduces the section open to flow and, due to the viscosity increase, causes a decrease of the ability of the polymer melt to fill the cavity. This issue is particularly significant for micro-injected parts in which high aspect ratios are precluded because of premature solidification. In this work, a system for rapid surface temperature control was designed, built and applied to a cavity for micro-injection molding. The system consists in an electrical resistive thin component and an insulation layer and can increase the mold surface temperature of some tenths of a degree Celsius in a time of the order of one second. The system is versatile enough to allow the control of thermal histories during the whole process and at different positions inside the cavity. Injection molding tests were then carried out with this system by using a general purpose isotactic polypropylene and a cavity 200 mm thick in order to check the effect of surface heating on reachable flow length and morphology of the molded parts. The effect of mold temperature on the flow length was as expected dramatic on both the flow length and the obtained morphology: the samples molded with a high mold temperature presented a spherulitic morphology in the whole cross-section, while with a low surface temperature the spherulitic morphology was detectable only at the positions close to the midplane whereas the layer closer to the surface present a very oriented structure due to flow taking place at low temperature.

1. Introduction

Micro-injection molding is a technology for high value added products of increasing application in the areas of medical technology, as components of optical systems, as micro parts in microfluidics, biotechnology, and electronics (Giboz et al., 2007). Although the concept of micro-part has many interpretations, Whiteside et al. (Whiteside et al., 2004) consider that, depending on the areas of interest, a micro part should present one of the following three characteristics:

- a weight of a few milligrams
- features with dimensions in the micrometer scale
- tolerances in the micrometer scale.

The reduction of part dimensions introduces additional issues with respect to conventional injection molding, together with the advantage of the most efficient process for the large-scale production. The cavity thickness is the decisive parameter to the molding of small parts as reported by Song et al. (Song et al., 2007).

The control of mold temperature is important in the injection molding process, and a crucial feature for micro parts. Ideally, the temperature should be higher than solidification point during filling, in order to allow a complete filling without an excessive pressure and stress on the material; after filling, the temperature should quickly decrease below the solidification point to obtain a solid polymeric part in reasonable times (Jansen and Flaman, 1994). Therefore, a high temperature during filling has been reported to improve the surface appearance (Zhao et al., 2011), to reduce the weld lines (Wang et al., 2013) and to increase the replication quality (Meister et al., 2015). The control of cooling rate after filling is also critical for the morphology (e.g., degree of crystallinity or orientations as reported by Liparoti et al. (Liparoti et al., 2015)) and thus mechanical properties (e.g. tensile strength as reported by Pantani et al. (Pantani et al., 2005)). The surface quality in replicating micro-

* Corresponding author.
E-mail address: fedesantis@unisa.it (F. De Santis).

http://dx.doi.org/10.1016/j.jmatprotec.2016.05.023

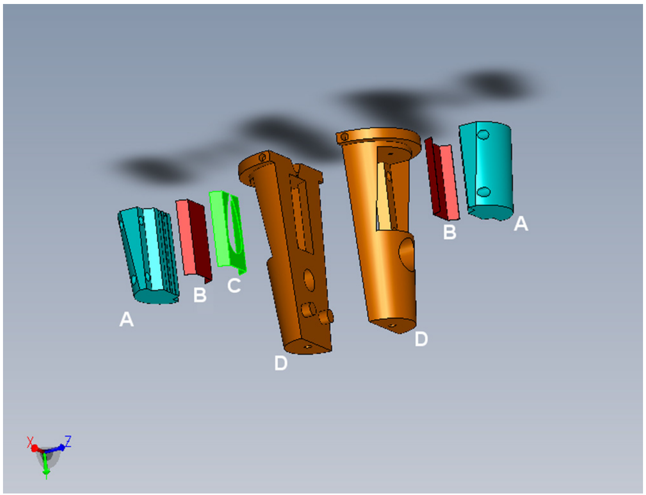

Fig. 1. Exploded view drawing of the elements composing the mold. (A) inserts; (B) heated slabs; (C) cavity; (D) main mold halves.

features is one of the most important process characteristics and constitutes a manufacturing constraint in applying injection molding in a range of micro-engineering applications (Sha et al., 2007). In particular Lucchetta et al. (Lucchetta et al., 2012) developed a technology for rapid heating and cooling of injection molds to analyze the effect of fast variations of the mold temperature on the improvement of micro features replication and moldings appearance.

Despite the huge literature dedicated to the effect of mold temperature on standard injected molded samples, only limited attention was devoted to the micro-injection molding. Attia and Alcock (Attia and Alcock, 2010) investigated the developments that have been achieved in different aspects of micro-injection molding of microfluidic devices. Further attempts have been made to meet this objective and reviews of the methods can be found in the literature. Yao et al. (Yao et al., 2008) offer a constructive overview on the state of the art in mold rapid heating and cooling, with the goal of explaining the working mechanisms and providing unbiased accounts of the pros and cons of existing processes and techniques. Among the several possibilities, the so-called “coating heating”, namely the possibility of heating just the surface of the mold by means of thin electrical resistances, presents many advantages: the optimal use of heating power (since just the needed part of the mold is heated) and the possibility of a temperature control. The rapidity of the temperature evolution is obviously crucial, as recently indicated by Berger et al. (Berger et al., 2014). To overcome the difficulties to fill a thin-wall cavity with long flow paths also special resins (e.g. DSM Akulon Ultraflow polyamide 6) with high flow properties were developed.

In this work, a novel system for controlling the surface temperature of a mold for micro-injection molding has been developed to overcome the limitations of the available technologies and it has been used to analyze the effect of fast variations of the mold temperature to the injection molding of a polypropylene in a 200 μm thick cavity.

The potential processing benefits of the proposed system go from increased productivity (cycle time reduction) to increased freedom of design (flow improvement), as well as increased quality levels (surface appearance, weldability) in the finished part.

2. Experimental

2.1. Design and realization of the mold

The injection molding machine adopted in this work is an HAAKE Minijet II by Thermo Scientific. This machine is a mini-injection molding system, that adopts a pneumatic piston to control the pressure during the molding. The molds for HAAKE Minijet II present a truncated cone shape, with a diameter which changes from 50 mm (at the gate side) to 35 mm over a length of about 90 mm.

Starting from the standard truncated cone shape of the molds used with HAAKE Minijet II, a novel system consisting in a mold with inserts and heating elements was designed, as shown in the exploded view drawing in Fig. 1, and carried out. The implemented heating structure is based on very thin wire resistances, sealed in a carrier medium composed of polyimide film, each of them having the following characteristics: $R = 120\,\Omega$, length = 3.8 mm, width = 5.0 mm, thickness = 50 μm (volume, $V_R = 0.95\,mm^3$). These heating resistances were positioned in a 5 × 2 matrix, as shown in the right part of Fig. 2, in order to cover a rectangular surface next to the cavity covering a surface about 8 mm wide and 20 mm long, and fixed on a steel slab 200 μm thick, as shown on the left part of Fig. 2. The thickness of the steel slab, which will constitute the cavity surface, was chosen in order to impart mechanical resistance and at the same time to allow for a fast heating and cooling. All the wire

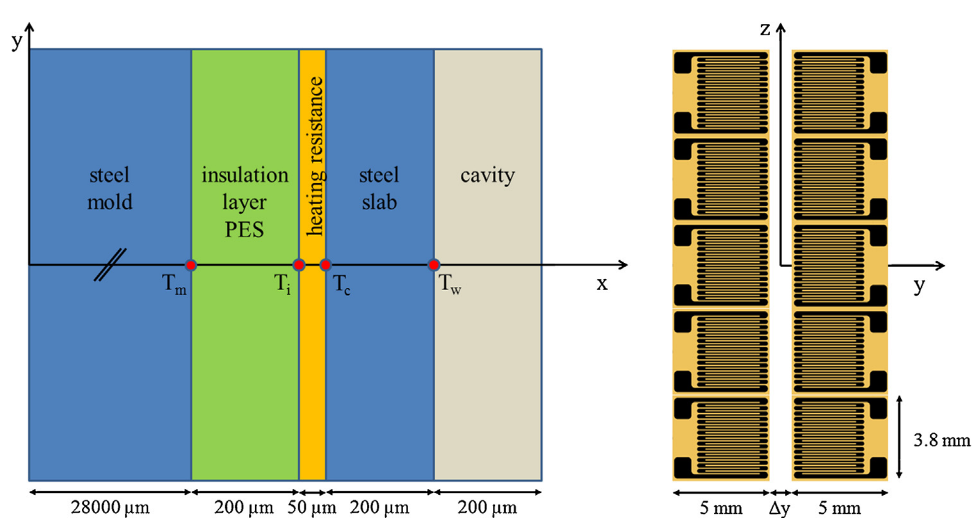

Fig. 2. Schematic of the layers on the left, with specific position for calculated temperatures: T_m between mold and insulation layer, T_i between insulation layer and heating resistances, T_c between heating resistances and steel slab, and T_w between steel slab and the cavity. Schematic of the heating resistances 5 × 2 matrix on the right.