Applied Thermal Engineering 130 (2018) 865–876

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

Evaluation of heat transfer at the cavity-polymer interface in microinjection moulding based on experimental and simulation study

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HIGHLIGHTS

- High speed IR camera used to measure melt cooling during the micromoulding cycle.
- Effects of surface topography on cooling through laser machined sapphire windows analysed.
- Experimental and simulation data compared to determine HTC value.
- Higher value of HTC improves cooling prediction for microinjection moulding.

ARTICLE INFO

Article history:
Received 27 February 2017
Revised 10 August 2017
Accepted 5 November 2017
Available online 8 November 2017

Keywords:
Heat transfer coefficient
Microinjection moulding
Polymer cooling
Simulation
Moldflow

ABSTRACT

In polymer melt processing, the heat transfer coefficient (HTC) determines the heat flux across the interface of the polymer melt and the mould wall. The HTC is a dominant parameter in cooling simulations especially for microinjection moulding, where the high surface to volume ratio of the part results in very rapid cooling. Moreover, the cooling rate can have a significant influence on internal structure, morphology and resulting physical properties. HTC values are therefore important and yet are not well quantified. To measure HTC in micromoulding, we have developed an experimental setup consisting of a special mould, and an ultra-high speed thermal camera in combination with a range of windows. The windows were laser machined on their inside surfaces to produce a range of surface topographies. Cooling curves were obtained for two materials at different processing conditions, the processing variables explored being melt and mould temperature, injection speed, packing pressure and surface topography. The finite element package Moldflow was used to simulate the experiments and to find the HTC values that best fitted the cooling curves, so that HTC is known as a function of the process variables explored. These results are presented and statistically analysed. An increase in HTC from the standard value of 2500 W/m^2 C to values in the region 7700 W/m^2 C was required to accurately model the observations.

1. Introduction

Microinjection moulding is a leading technology for manufacturing polymer micro components in large quantities at a relatively low cost. Typically, masses of the final products can be less than 100 mg having dimensions in a micrometre range [1]. During the microinjection moulding cycle the polymer undergoes a complex process where it is heated to its melt temperature, injected at high velocity and high pressure into a cavity, where it cools down and solidifies into a final product. The heat transfer between the tool surface and the polymer melt has a significant influence on the filling and cooling behaviour. The flow of heat across this interface can influence the component form, surface properties, internal morphology, residual stresses and the dependent physical properties. This heat transfer is governed by the thermal contact resistance (TCR) or thermal contact conductance (TCC), (which is the inverse of the TCR) and is affected by the area of the contacting surfaces, the temperature of the polymer and mould, the pressure applied and the surface topography. Commercially available simulation software products use the term heat transfer coefficient (HTC) which is the same as the TCC.

The TCC is defined as the ratio of the heat flux (Q/A) to the additional temperature drop (ΔT) due to the presence of the imperfect joint and is defined as [2]:

$$TCC = Q/A\Delta T \ (W/m^2 \cdot K) \quad (1)$$

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https://doi.org/10.1016/j.applthermaleng.2017.11.022
1359-4311/

Heat flow through the interface of the contacting surfaces can be split into the three forms, namely conduction through the contact spots, conduction through the microscopic or macroscopic voids between the actual contact spots (which can be filled with different conducting substances such as air, other gases, coatings and greases) and radiation across the gaps (which can be ignored if the temperature at the interface is lower than 400 °C). Convection can be disregarded because the interfacial gap thickness is so small [2–4].

The heat transfer at polymer/metal interfaces has been studied previously by a number of researchers. Steady state experiments were performed by Marotta and Fletcher [5], Narh and Sridhar [6] and Dawson et al. [7] using an axial heat flow apparatus, described elsewhere [8]. Results were reported for a range of polymers and range of substrates. The HTC values were varying between 250 and 1659 W/m^2 K in the work of Marotta and Fletcher [5], 15,000 and 25,000 W/m^2 K in the work of Narh and Sridhar [6] and around 7000 W/m^2 K in the work of Dawson et al. [7]. The suggested values of HTC at metal-polymer interfaces in [5–7] were obtained on solid polymer samples through steady state experiments, with relatively low applied pressures when compared with those typically seen in microinjection moulding.

In conventional injection moulding Yu et al. [9] determined HTC values for Acrylonitrile butadiene styrene (ABS)/steel interfaces with sample thicknesses in the range of 2–4 mm and showed the HTC dependence on material properties, processing conditions and the thickness of the part. Sridhar and Narh [10] through their work showed that HTC is transient, which was confirmed in later study by Sridhar et al. [4]. Delaunay and Le Bot [11] have proven experimentally that constant mould temperature cannot be used as a boundary condition for injection moulding simulation and perfect contact between the polymer and the mould cannot be assumed either. When the cavity pressure reaches zero a sudden decrease in HTC occurs, which can be explained by considering the gap formation between the cavity wall and the polymer surface due to shrinkage of the polymer part. Observation in the work of Sridhar et al. [4] and Delaunay and Le Bot [11] were confirmed by Bendada et al. [12–13], who have designed a novel system for measuring polymer temperature during the injection moulding cycle and have shown in their work that HTC does not change when high pressure is applied, but when pressure drops to zero, HTC suddenly decreases. Masse et al. [14] studied the cooling stage of polymer within an injection moulding process, taking into account parameters such as HTC, residual stresses, and the PvT diagram. They have tested three surfaces with different roughness (Ra = 0.05 μm, Ra = 1 μm, Ra = 5 μm) at different pressures. Results showed that HTC decreases when roughness increases.

Up to this point all the experimental work was conducted using conventional injection moulding machines and on relatively large parts with wall thicknesses greater than 1 mm. A limited amount of research has considered HTC in microinjection moulding. Nguyen-Chung et al. [15] focused on determination of HTC during the filling stage in microinjection moulding through a short-shot study on parts with wall thicknesses of 0.2 mm and 0.5 mm. The experimental work showed that cavity pressure, thickness of the cavity and injection speed has an effect on HTC. Values of the heat transfer coefficient for thicker components were lower compared with the thinner micro-spirals. For the thicker micro-spirals HTC was varying between 0 and 8000 W/m^2 K, whereas for the thinner sections it was in the range of 1500–25000 W/m^2 K. Somé et al. [16] focused their work on developing a model for prediction of HTC values in a steady state with varying pressure or in transient condition but with constant applied pressure. HTC values for polypropylene (PP) and ABS in contact with steel, chromium and polytetrafluoroethylene (PTFE) were experimentally obtained and modelled. The effect of surface roughness (Ra = 0.05 μm, Ra = 1 μm and Ra = 5 μm) was also investigated. It was shown that thermal conductance is higher for smooth surfaces and lower for rough surfaces. ABS/Steel HTC values for several surface roughnesses were varying from approximately 600–1600 W/m^2 K, PP/steel interfaces 600 – 10,000 W/m^2 K and ABS/steel, ABS/chromium and ABS/PTFE 900–1500 W/m^2 K. Liu and Gehde [17] focused their work on evaluation of HTC at the mould/polymer interface to improve the cooling and crystallinity simulation. The HTC values were determined for LDPE taking into account three different melt temperatures, three injection rates and three surface roughnesses, namely Ra = 0.01 μm, Ra = 1.36 μm and Ra = 5.81 μm. It was shown that the HTC increases with raising melt temperature and injection rate. It has to be noted that thickness of the part was 2 mm and was the same thickness that was used in Ref. [16], however the effects of the surface roughness reported were the opposite to those reported by Somé et al. Reported values of HTC were between 18,750 and 22,500 W/m^2 K for Ra = 0.01 μm, 26,000 – 33,000 W/m^2 K for Ra = 1.36 μm and 28,750 – 34,000 W/m^2 K for Ra = 5.81 μm. Hong et al. [18] determined HTC values at nickel/PMMA interface through a short-shot study measuring the filling height of the patterns on 1.12 mm thick samples with cylindrical micropatterns of 30 μm in diameter and 14 μm in height. The HTC values varied between 2300 and 10,000 W/m^2 K. At the present time, the availability of data to determine HTC in microinjection moulding is limited and despite its importance in solidification prediction it remains poorly understood.

A number of standard boundary condition values are used in injection moulding simulations, which may be unsuitable for microinjection moulding simulation and the heat transfer coefficient is one of them. The HTC values typically used in simulation were obtained from experiments performed with conventional injection moulding and typically with cavity thickness above 1 mm. Moreover, in the software, the HTC is assumed to have a constant value and then it cannot adequately describe the flow through micro channels [19].

In this study we have taken a novel approach in determination of HTC values for microinjection moulding. The work has included bespoke experimental mould design and manufacturing, materials characterisation, infra-red temperature measurements, and cooling analysis prediction using commercial simulation software.

We shall derive values of HTC as a function of mould surface topography, melt and mould temperature, injection speed and packing pressure. This will enable us to evaluate the effects that the customary assumption of a constant HTC value would have on the validity of micromoulding simulations. This has implications for injection moulding in general.

2. Experimental

In order to study polymer cooling directly, a special mould was designed based on a flow visualisation tool previously developed at the University of Bradford [20]. A transparent sapphire window was used as one half of the mould cavity. The fixed half of the mould was fitted with a 45° first surface mirror, which enabled visibility within the cavity through the sapphire window. The cavity pressure was measured using a Kistler 6189A p-T sensor (sensitivity = −6.450 pC/bar, linearity ≤ ± 0.15% full scale output) flush mounted in the centre of the cavity of the moving part of the mould.

2.1. Sapphire

The thermal properties of sapphire are very similar to P20 mould steel. Specifically, the thermal conductivity at 20 °C is 29 W/mK for P20 tool steel and 23 W/mK for sapphire. The specific