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A. Bendada [*], A. Derdouri, M. Lamontagne, Y. Simard

National Research Council Canada, 75 De Mortagne, Boucherville, Que. J4B 6Y4, Canada

Abstract

The objective of this work is to combine experimental and numerical approaches to evaluate the nature of thermal contact between polymer and mold through the different phases of a typical injection cycle. The key idea of this analysis is the simultaneous use for the first time of an infrared hollow waveguide pyrometer and a two-thermocouple probe specially devised for this study. The infrared waveguide pyrometer is used for the on-line monitoring of the temperature at the surface of the polymer within the cavity, while the two-thermocouple probe is used to determine via an inverse problem the local heat flux crossing the polymer–mold interface and the temperature at the cavity surface. Subsequently, a second inverse algorithm, which combines the latter estimated data and the temperature at the polymer surface measured with the infrared waveguide device, allows the determination of the thermal contact resistance. The results show that the thermal contact resistance between polymer and mold is not negligible, not constant with time, and strongly correlated with process conditions.

1. Introduction

Injection molding of thermoplastic objects is a cyclic fabrication method that involves complex fluid flow and heat transfer coupled with phase change. Although, the same steps of the process are repeated regularly, they are inherently transient. First, an accurately sized shot of a pre-heated

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[*] Corresponding author. Tel.: +1-405-6415241; fax: +1-450-6415106.
E-mail address: abdelhakim.bendada@nrc.ca (A. Bendada).

molten polymer is rapidly injected through a small orifice or gate in a cold mold cavity having a more or less intricate geometry. As thermoplastics, and more importantly semi-crystalline thermoplastics, shrink while cooling, a packing/holding pressure is applied to compensate for shrinkage by adding more molten material until the gate is frozen. When solidification of the injected polymer is deemed sufficient, the mold is opened and the part is ejected. Finally, the mold is closed and is ready for the next cycle to start. During the cooling phase, after the gate has frozen, the cavity pressure drops to its minimum value and an air gap between polymer and mold due to shrinkage is formed, giving rise to a significant change in heat transfer behavior at the polymer/mold interface. The detachment of the part plastic from the cavity was monitored using an ultrasonic pulse-echo technique [1] and was shown to correspond to a slight change in the slope of the decreasing cavity pressure. Some commercially available software packages assume, however, that the polymer–metal contact is perfect and use the mold internal surface temperature as a boundary condition for the polymer at the same surface. In these conditions, the simulation results predict lower cooling times than observed in practice. Other software packages provide for the use of a constant rather than a time dependent heat transfer coefficient. Even then, numerical values of the heat transfer coefficient are not readily available for many polymers, and the user is left with estimates taken from the literature [2]. The purpose of this article is to investigate the thermal contact between polymer and mold during a typical injection cycle and its evolution with the molding conditions.

As mentioned above, when shrinkage develops during the cooling phase, the real contact between the solidifying polymer and the mold does not occur along the nominal surface shared by both media but only on a few areas. The residual space, or air gap, does not conduct heat as efficiently as when intimate contact is maintained. The heat flux may thus use these two distinct ways to cross the interface. This gives rise to the so-called thermal contact resistance (TCR) characterized by a sharp drop in temperature at the interface and which may be defined per surface unit as $\text{TCR} = (T_{\text{ps}} - T_{\text{ms}})/\varphi$, where T_{ps} is the polymer surface temperature, T_{ms} is the mold surface temperature, and φ is the heat flux density crossing the interface. TCR may vary with pressure and temperature, with the type of metal used to make the mold, the surface roughness and the polymer in contact with the mold. During constant rate cooling of a thin molten polymer specimen in contact with colder wall TCR is an essential parameter for controlling the solidification front. In injection molding, the measurement of TCR and the prediction of its evolution with pertinent process parameters are very difficult. Indeed, there is a strong correlation between the polymer temperature, TCR, and the inside cavity pressure. A lot of attention was dedicated to rheological properties and flow behavior of molten polymers during processing, but much less to thermal aspects during cooling and solidification. Few researchers have investigated the problem of TCR in injection molding [3–7], and all the undertaken studies agree with the following assumptions: TCR between polymer and mold is not negligible for the prediction of temperature field in injected polymer parts; TCR is not constant during the molding cycle. Yu et al. [3] determined TCR in an injection mold using temperature measurements obtained by thermocouples embedded near or at the cavity surface and which they assigned to the polymer surface. Also, it is not clear how they determine the heat flux density at the mold/polymer interface. Kamal et al. [4] calculated a heat transfer coefficient (inverse of TCR) for polypropylene, polyethylene and polystyrene using the TCR definition given above. The polymer temperature at the interface and the mold temperature were measured using one thermocouple mounted flush with the cavity

surface and another thermocouple at one millimeter from it, respectively. The heat flux density was obtained at a different location of the cavity, using a fast response heat flux sensor, equipped with an integrated thermocouple to give another measurement of the melt temperature at the mold/polymer interface. The heat transfer coefficient calculated on the basis of the polymer surface temperature using a flush thermocouple was lower by a factor of 2–3 than when calculated on the basis of the heat flux sensor temperature. This is a clear indication that polymer surface temperature direct measurements using standard thermocouples are not reliable. Thermocouples tend to behave as fans and locally cool the polymer. Rhee et al. [5] constructed an experimental apparatus to investigate the global TCR of a thin heated sheet of plastic in sandwich between two steel blocs. Narh and Sridhar [6] used the same approach to additionally study the effect of pressure on TCR. However studies were conducted in steady state conditions and relied on linear extrapolation for their estimate of TCR. More recently, Delaunay et al. [7] used temperature measurements in the mold close to the mold/polymer interface to calculate the mold surface temperature T_{ms} and the heat flux density φ at the interface using an inverse problem approach. The polymer temperature at the interface was obtained as part of the solution to the heat transfer problem through the thickness of the part during the packing and cooling phases. An interesting finding of their work is the fact that the part detachment from the mold induces a reheating of the polymer surface. In this work we will confirm this observation by a direct measurement of the polymer surface temperature. As mentioned above, the temperature readings from thermocouples mounted flush with the mold cavity cannot be assumed polymer surface temperature during the whole injection molding cycle because of imperfect contact. To overcome this problem, we suggest in this work a new methodology to get accurate and reliable temperature monitoring at the surface of the polymer at the interface. The key feature of the proposed method is the use of a hollow optical waveguide that is incorporated into the injection mold to transmit the thermal radiation from the target to a photon detector [8]. The other physical parameters needed for the determination of TCR, namely the mold surface temperature and the heat flux density, are indirectly obtained with the use of a specially designed two-thermocouple probe similar to the one developed by Delaunay et al. [7], and the solution of an inverse heat conduction problem. The two-thermocouple probe provides temperature histories at two different locations within the mold, close to the mold surface, situated on a line normal to the cavity surface. Then, these in-mold temperatures are introduced into an inverse algorithm to determine the mold surface temperature and the heat flux density that crosses the interface. From the data provided by the infrared pyrometer and the two-thermocouple probe, it is possible to estimate the TCR evolution for various process conditions. The determination of TCR and how it is affected by process parameters such as injection pressure, injection temperature, and mold temperature are addressed.

2. Experimental

2.1. Injection molding set-up

Experiments were carried out on a 400-ton Husky injection-molding machine. The experimental part has the shape of a box with the main average dimensions are $330 \times 200 \times 180$ mm and a thickness of 2.3 mm. With such dimensions, a one-dimensional heat conduction through the

part thickness into the mold in locations far from the part features (such as ribs and bosses) is a valid assumption. To keep the mold temperature as uniform as possible a cavity temperature controller with heated circulating oil was used. The material used in the experiments was polypropylene. It was selected because it was opaque at the spectral bandwidth of the hollow waveguide pyrometer [8] and highly sensitive to temperature and inside cavity pressure changes. Shrinkage and warpage phenomena are in general quite significant for polypropylene during injection molding [7].

Fig. 1 is a close up image of the relative locations of three probes that were flush mounted with the cavity surface to monitor different process parameters. The infrared waveguide probe was incorporated at a central position. On its right-hand-side at a distance of 18 mm, a D.M.E SS405C pressure transducer was also incorporated to monitor the inside cavity pressure. The two-thermocouple probe was set at the left-hand-side of the waveguide probe at a distance of 20 mm. Data acquisitions for both infrared, pressure and temperature sensors were performed simultaneously at a frequency rate of 500 Hz so that rapid and sudden signal changes could be observed.

Eight series of experiments were undertaken for different combinations of holding pressure, mold temperature, and melt injection temperature. The plastication conditions were set so that an injection temperature of 220 or 275 °C was achieved; the mold temperature was regulated at 25 or 50 °C, while the hydraulic pressure during holding was set to 2.5 or 16 MPa. The injection rate was 11 cm/s, the packing time was 1.75 s, and the holding time was 3.5 s. The cooling time in the cycle was set relatively long, 70 s, in order to be able to investigate the thermal contact in low-temperature ranges before the point of ejection. During the experiments, the operating parameters
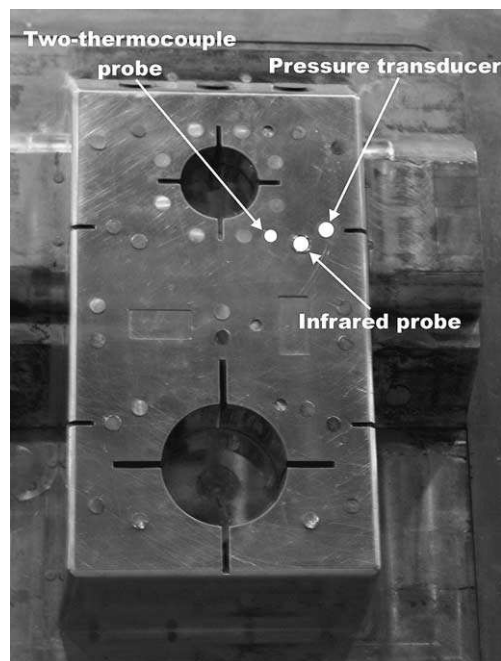

Fig. 1. Close up on the mobile-side of the injection-mold showing with white circles the locations of the infrared probe, the pressure transducer, and the two-thermocouple probe.

such as injection temperature, hydraulic pressure, mold temperature, and extrusion screw movement were also carefully monitored. All the recorded tests were done after the mold reached a thermally stable condition.

2.2. Measurement procedure of the temperature at the polymer surface

The temperature at the surface of the polymer stream is a required boundary condition to determine the TCR value. As previously mentioned, it was non-intrusively monitored with a hollow waveguide pyrometer that was developed for injection molding operations. Bendada et al. [8] have already described the waveguide pyrometer elsewhere and only a brief description is given here. The main component of the pyrometer is the optical hollow waveguide which gathers the thermal radiation emitted from the hot polymer through a sapphire window and transmits this energy to an infrared detector. The detector converts the radiation into an electric signal and in turn transmits it via long electric cables to a signal-processing unit. The waveguide consists of silver and fluoro-carbon-polymer (FCP) films deposited on the inside of a smooth glass sup-porting tube. The main characteristic of this type of waveguides is their low transmission loss of the thermal energy in the mid- and far-infrared. This allows the measurement of quite low tem-peratures, as low as room temperature. Furthermore, by the insertion of appropriate narrow-band-pass filters in the optical path of the waveguide pyrometer, it is possible to accurately measure the polymer surface temperature. Conventional optical fiber thermometers can neither measure such low temperature ranges nor measure the polymer surface temperature. We should mention here that like most radiometric thermometers, it was necessary to find out the emissivity of the polymer under investigation. Indeed, the infrared energy radiated by an object does not depend only on its absolute temperature, but also on its emissivity. To retrieve the true absolute temperature, emissivity must be known. Since the reflectance is typically 3% for most plastics throughout the infrared spectral region [9], according to Kirchhoff's law and conservation of radiant energy considerations [10], emissivity was considered to be around 97% in the afore-mentioned measurement procedure.

2.3. Procedure for estimating the heat flux and the temperature at the cavity surface

Besides the polymer surface temperature, the other two physical parameters required to determine the TCR value are the temperature at the surface of the cavity and the heat flux crossing the polymer–mold interface. They were both obtained via the use of the two-thermo-couple probe. The latter was composed of two steel half-cylinders joined side by side. These were obtained by cutting longitudinally a cylinder that was 8 mm in diameter and 130 mm long. The shape and size of the cylinder tip in contact with the polymer stream were designed to fit com-monly employed probe-housing cavities in injection molds. Two E-type fine-wire thermocouples 75 μm in diameter were spot-welded inside and along the axis of the cylindrical probe at two different locations (1 and 2 mm) from the probe tip. At the interface between the two half-cylinders, a narrow slot was longitudinally machined in one half-cylinder to contain the ther-mocouples wires. Two thermocouples rather than a single thermocouple were utilized because the additional information could aid in more accurately estimating the surface conditions via the sequential procedure detailed thereafter. To perform perfectly non-intrusive measurements, the

two-thermocouple probe was manufactured with the same steel (P20 steel grade) as the mold material and the same roughness as the cavity surface. Two 3B47-conditioning modules from Analog Devices Company amplified the thermocouple signals to a data acquisition system and control unit. The latter devices were piloted with a computer via a GPIB card. The 3B47 module allowed the automatic conversion of the monitored voltage to temperature. A signal processing software, Labtec, was used for the visualization and the exploitation of the experimental results.

Close to the polymer–mold interface, heat transfer in the mold can be assumed to be one-dimensional. The temperature field can thus be described by the variable $T(x, t)$. The mold is considered as a semi-infinite body (defined by $x \geqslant 0$) initially at temperature T_0; for times $t > 0$ there is heat generation at the mold surface ($x = 0$) at a rate of $q(t)$ per unit time, per unit surface. The mathematical formulation of this problem is given as

$$\frac{\partial^2 T(x,t)}{\partial x^2} = \frac{1}{\alpha} \frac{\partial T(x,t)}{\partial t} \quad \text{in } 0 < x < \infty, \ t > 0, \tag{1}$$

$$-\lambda \frac{\partial T}{\partial x} = q(t) \quad \text{at } x = 0, \ t > 0, \tag{2}$$

$$T = T_0 \quad \text{for } t = 0, \ \text{in the region,} \tag{3}$$

where α and λ are the thermal diffusivity and thermal conductivity of the mold material, respectively. The exact solution of the temperature field $T(x, t)$ can be analytically calculated with the use of Duhamel's theorem [11].

From temperature histories monitored with the two-thermocouple probe, a regularized sequential inverse method allows the estimation of both heat flux crossing the polymer–mold interface and temperature at the cavity surface. This data processing is based on J.V. Beck's method that uses a combination of the function specification method and the future time steps concept. It may be applied for one or a few micro-thermocouples. The detailed description of the method has been presented elsewhere [12,13], and only a brief account is given here.

In the function specification approach, the entire period in which the polymer is in contact with the mold is divided into a finite number of time intervals. The heat flux varies from one interval to another, but a constant value q_M is assumed within each individual interval $[t_{M-1}, t_M]$. The estimated heat flux components $q_1, q_2, \ldots, q_{M-1}$ are assumed to be known and the objective is to estimate q_M. In order to add stability to the inversion algorithm, the future time steps procedure is utilized as well. It assumes temporarily that several future heat fluxes are constant with time. Hence r future heat flux components are temporarily made equal. The optimized value of the heat flux is obtained in a sequential manner by increasing M by one for each time step in the following expression:

$$q_M = \frac{\sum_{i=1}^{r} \sum_{j=1}^{J} (Y_{j,M+i-1} - T_{j,M+i-1}|_{q_M = \cdots = q_{M+i-1} = 0}) Z_{ji}}{\sum_{i=1}^{r} \sum_{j=1}^{J} Z_{ji}^2}. \tag{4}$$

In this equation, the first subscript, j, refers to space (sensor number) and the second to time. There are r future times and J temperature sensors. $Y_{j,M+i-1}$ refers to a measured temperature by sensor number j at the time interval $[t_{M+i-2}, t_{M+i-1}]$, while $T_{j,M+i-1}$ is the exact temperature calculated by solving the forward problem, Eqs. (1)–(3), at the same location and time interval when fluxes $q_M, \ldots, q_{M+i-1}$ are set to zero. The quantities Z_{ji} are defined by

$$Z_{ji} = \sum_{k=0}^{i-1} X_{j,M+k}(t_{M+i-1}), \tag{5}$$

where $X_{j,M+k}(t_{M+i-1})$ represents the sensitivity coefficient of temperature calculated at the location of sensor number j at time t_{M+i-1} with respect to a heat flux component q_{M+k}, and is defined as

$$X_{j,M+k}(t_{M+i-1}) = \frac{\partial T_{j,M+i-1}}{\partial q_{M+k}}. \tag{6}$$

The choice of the number of future times r is an important parameter for stabilizing the algorithm. Suitable conditions to choose r as a function of sampling time step and magnitude of measurement noise are given by Reinhardt [14]. Although the heat fluxes are temporarily assumed to be constant for a period involving r future time steps, once the optimized value is obtained, it applies only for the time interval $[t_{M-1}, t_M]$. After the determination of the surface heat flux components, the surface temperature is simply calculated with the analytical solution of the forward problem described by Eqs. (1)–(3).

3. Results and discussion

3.1. Temperature at the polymer surface

During filling, holding and cooling under pressure a good contact is ensured between the polypropylene and the mold, so the heat transfer occurs across a small TCR. During the cooling, as the solidification progresses, the part begins to shrink through its thickness and an air gap is likely to be formed at the polymer–mold interface. After a sizable gap is developed, the interface returns to the steel–air condition, and therefore, the pressure drops back to its minimum level. Fig. 2 shows a typical cavity pressure trace obtained for a mold temperature regulated at 25 °C, an injection temperature of 220 °C, and a hydraulic pressure of 2.5 MPa during holding. In the cavity, the packing/holding pressure was measured to be about 38–40 MPa. As soon as the pressure becomes equal to zero (at ~12 s), the heat transfer near the interface is disturbed by the air gap appearance and leads to a sudden rise of the surface temperature decay signal. This deviation is illustrated by Curve (1) in Fig. 3. As long as the part skin is in good contact with the cavity wall, heat coming from the part core is evacuated and the polymer temperature at the mold–part interface decreases monotonically. When the part detaches from the mold, the heat that is still being conducted from the core through the part thickness results in a temporary increase of the polymer surface temperature. After about 8 s, it starts decreasing again for the rest of the cooling time, albeit at a slower rate due to the presence of the air gap. The arrow in Fig. 3 indicates the time needed for the polymer to separate from the mold for the above mentioned operating conditions, which subsequently results in abrupt changes of pressure and temperature readings.

3.2. Heat flux and temperature at the cavity surface

Typical evolutions of temperature in the mold, i.e. temperatures measured with the two-thermocouple probe, are represented by Curves (2) and (3) in Fig. 3. Curve (2) refers to the
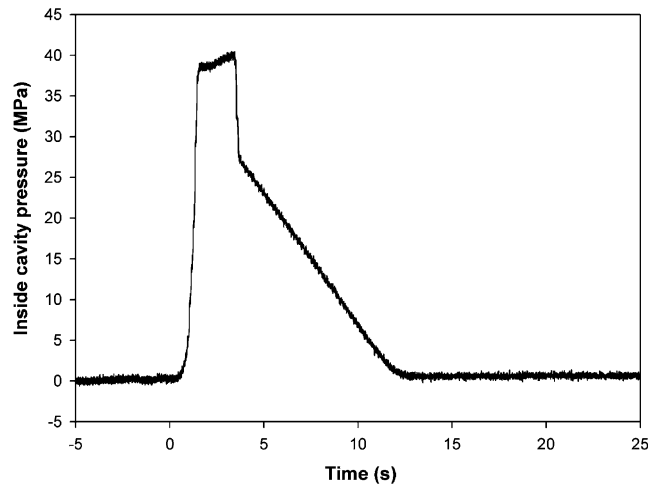
Fig. 2. Typical inside cavity pressure as a function of time as recorded for an injection temperature of 220 °C, a mold temperature of 25 °C, and a hydraulic pressure of 2.5 MPa.
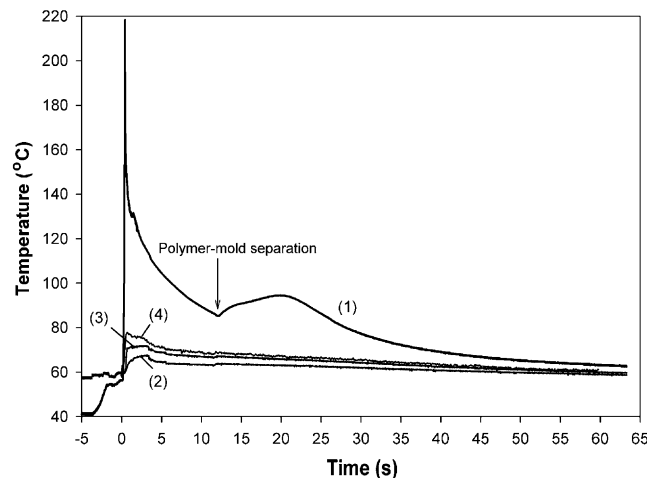

Fig. 3. Temperature traces in the mold and at the surface of the polymer stream: (1) temperature at the polymer surface; (2) temperature in the mold at 2 mm from the interface; (3) temperature in the mold at 1 mm from the interface; (4) temperature at the surface of the mold calculated with the inverse method. Same operating conditions as for Fig. 2.

thermocouple located at 2 mm from the mold cavity surface, while Curve (3) refers to the thermocouple located at 1 mm from the same surface. These thermocouples data are obtained for the same operating conditions as the inside cavity pressure reported in Fig. 2, and the polymer surface temperature presented with Curve (1) in Fig. 3. As previously noted, the mold surface temperature and heat flux crossing the interface are not measured in-line but are indirectly calculated from the thermocouples data via the inverse heat conduction approach described in Section 2.3. The thermophysical properties of the mold material used in the inverse processing were characterized

via laser flash [15] method and a modulated differential scanning calorimeter (MDSC). The estimated values were 7800 kg m^{-3} for the density, 29.0 W m^{-1} °C^{-1} for the thermal conductivity, and 460 J kg^{-1} °C^{-1} for the specific heat.

The mold surface temperature resulting from the inverse calculation is reported in Fig. 3 with Curve (4). The surface temperature varies in time and increases by almost 20 °C just after polymer injection. Hence, a constant mold temperature that is usually taken as boundary condition in injection molding modeling software may give rise to inaccurate heat transfer predictions. Furthermore, the heat flux crossing the polymer–mold interface also obtained from the inverse calculation is reported via Curve (1) in Fig. 4. This evolution in time is typical of injection molding cycles [7,16]. When the polymer flow front reaches the two-thermocouple probe, heat flux increases instantaneously first then decreases relatively slowly as the part cools down.

3.3. Thermal contact resistance

TCR history that results from the measured and calculated quantities in Sections 3.1 and 3.2, is reported as Curve (2) in Fig. 4. The magnitude of TCR is in good agreement with results reported in literature [2–7]. At short times, TCR does not change as long as high pressure is maintained inside the cavity. When the cavity pressure drops back to zero, a sudden rise in TCR is observed. The sudden rise of TCR is related to the appearance of the air gap caused by the polymer shrinkage. The effect of operating conditions on TCR is shown with relevant examples of TCR curves in Fig. 5. TCR curves have been smoothed for the sake of a clear graphical comparison analysis.

The effect of inside cavity pressure on the contact between polymer and mold can be clearly observed by comparing Curves (1) and (2) of Fig. 5. These curves refer to the experimental tests performed with a mold temperature of 25 °C, and an injection temperature of 220 °C. The only difference between process parameters is the hydraulic pressures used during holding (2.5 and
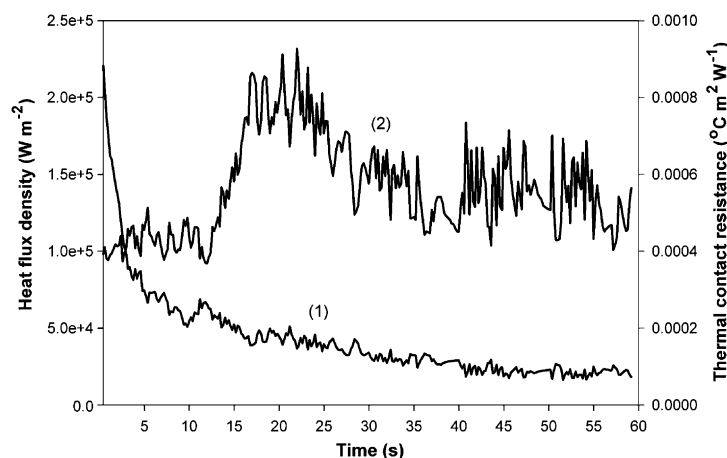

Fig. 4. Surface heat flux (1) calculated using the internal temperatures provided by the two-thermocouple probe, and calculated TCR (2). Same operating conditions as for Figs. 2 and 3.
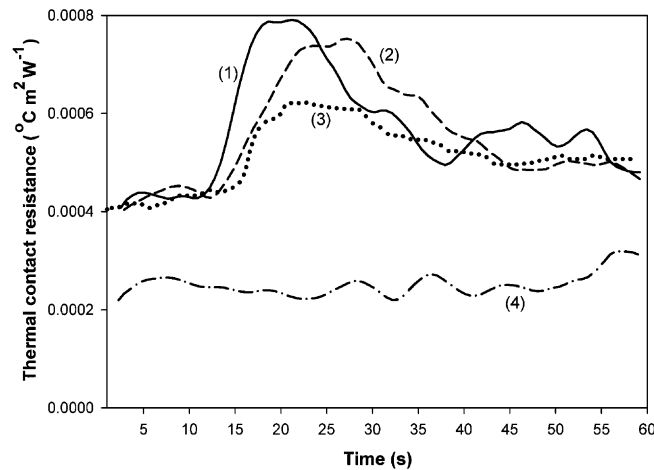
Fig. 5. Smoothed curves of calculated TCRs for four different process conditions.

16 MPa). Curves (1) and (2) reveal that TCR reduces when pressure increases. This lower TCR is due to the compressibility of the material. When the pressure is increased, more material can be packed into the cavity to compensate for the effects of the volume shrinkage. Subsequently, shrinkage reduces, resulting in a lower air gap.

The effect of injection temperature is reported in the same figure with Curves (1) and (3). These traces are obtained for a mold temperature of 25 °C, and a hydraulic pressure of 2.5 MPa. The only difference between process parameters for the latter curves is the injection temperatures used (220 and 275 °C). We first observe that the polymer stays in a longer contact when the melt temperature is higher. It can also clearly be seen from Fig. 5 that TCR is insensitive to the change in the melt temperature as long as the contact at the interface is maintained. When the polymer shrinks away from the cavity surface, TCR is higher when a lower injection temperature is used. When melt temperature increases, the viscosity of the polymer decreases and a closer proximity and a better conformity with the wall of the cavity is more likely. Also, the pressure loss at the injection gates will be reduced resulting in a higher-pressure level inside the cavity. Subsequently, more material can be packed into the mold cavity and as a consequence, volume shrinkage is reduced and a lower air gap results.

The effect of mold temperature is reported by Curves (1) and (4). The only difference between process parameters for the latter figures is the mold temperatures used (25 and 50 °C). These curves indicate that mold temperature has a similar effect as injection temperature. When mold temperature increases, volume shrinkage reduces and a lower air gap is formed. This latter gap formation results in a negligible TCR. Only a slight monotonic deviation can be observed at long times on the TCR history when mold temperature is high. Shrinkage is not large enough to completely separate the polymer part from the mold. It should be reminded here that this low TCR is obtained in unfavorable operating conditions: low hydraulic pressure, 2.5 MPa, and low injection temperature, 220 °C. Therefore, mold temperature is probably the most influent parameter on air gap development during injection molding.

4. Summary

In injection molding simulation software, many assumptions are often made in order to simplify the mathematical complexity of the non-isothermal transient flow and phase change problem. Among these assumptions, contact between polymer and mold is usually considered as perfect. In this article, we have thoroughly investigated the time evolution of the TCR for a polypropylene part. The study uses a combination of experimental and analytical procedures to determine the TCR value. The key feature of the undertaken procedure is the use of two particular sensors to determine the boundary conditions of the thermal problem at the polymer–mold interface. For the first time in injection molding, an infrared hollow waveguide pyrometer is employed to measure the temperature at the surface of the polymer skin within the mold cavity. Whereas, the mold surface temperature and the heat flux crossing the interface are indirectly determined with a non-intrusive two-thermocouple probe designed specially for this application. We use an inverse heat conduction algorithm to calculate the mold surface conditions from temperatures monitored inside the mold. The results clearly show that the TCR between polymer and mold changes with time. The lower viscosity level during filling and higher pressure during packing and holding facilitates a close proximity of the polymer with the cavity wall. Although, the contact does not cover the nominal area of the inside cavity, but only few points, TCR is low and relatively constant. As the polymer cools down, its viscosity increases and its surface becomes hard. Cooling also causes volume contraction of the molded part inducing its detachment from the cavity wall and widening the separation at the interface. Concurrently, TCR starts to increase up to a maximum then falls off as the difference between the polymer surface temperature and the cavity wall temperature gets smaller and smaller. The rise in TCR corresponds to the experimentally observed polymer surface reheating after the air gap sets in. The results show that TCR is strongly dependent on the molding conditions: higher melt and mold temperatures as well as holding pressure result in a better heat transfer. i.e. a low TCR. When TCR rises after a gap formation at the polymer–mold interface, the cooling rate of the plastic part reduces which results in a longer cooling time and injection cycle. More work needs to be carried out to understand the heat transfer mechanisms at the polymer/metal interface in order to minimize the cycle time while achieving the desired part properties.

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