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CHARACTERIZATION OF THERMAL CONTACT IN INJECTION MOLDING VIA THE COMBINATION OF AN INFRARED HOLLOW WAVEGUIDE SYSTEM AND A TWO-THERMOCOUPLE PROBE

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Abstract: Flow of a molten polymer within the confining walls of a mold during injection molding is a complex phenomenon. The complexity stems from various sources: transient process, material nature, thermal effect, phase change, shrinkage, among others. Numerical simulation of this type of flow is very helpful in optimizing the mold design and processing conditions, but generally lacks appropriate knowledge of the thermal contact resistance (TCR) that is characteristic of the heat transfer across the interface between the polymer and mold-cavity. In this work, we aim to analyze the nature of thermal contact between polymer and mold through the different phases of a typical injection-molding cycle. The key idea is the combination of two measurement techniques: an infrared hollow waveguide device is employed for the first time to monitor the temperature at the surface of the polymer stream within the cavity, while a two-thermocouple probe is used to determine via an inverse heat conduction processing the heat flux crossing the polymer-mold interface and the temperature at the cavity surface. In a second part of the work, the data obtained with the infrared and the two-thermocouple instruments are used to determine TCR at the polymer-mold interface. The results show that TCR between polymer and mold is not negligible and not constant with time. The effect of packing pressure, melt and mold temperatures are investigated and discussed.

Introduction: Injection molding of thermoplastics 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 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. Excellent reviews of the subject can be found in the scientific literature [1-3]. While a great deal of attention has been given to the rheological and flow aspects during the filling stage, the solidification stage has been largely less considered. Modeling and simulation of the cooling phase of a molten polymer confined in the cavity of an injection mold rely on the use of realistic boundary conditions that in turn depends on the knowledge of the mechanisms by which heat is transferred between the polymer and the metal wall of the cavity. The heat transfer across the interface is described by what is called the thermal contact resistance (TCR). In most cases, this parameter is not known with precision but is rather empirical. During the cooling phase, after the gate has frozen, the cavity relative pressure can locally drop to zero resulting in the formation of an air gap between polymer and mold due to shrinkage. This gives rise to a significant change in the heat transfer mechanism at the interface. The purpose of this article is to investigate the thermal contact between polymer and mold during a typical injection molding cycle and its evolution with the molding conditions.

TCR is characterized by a sharp drop in temperature at the interface and may be defined per surface unit as $TCR = (T_{ps} - T_{ms}) / \varphi$, 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. Few researchers have investigated the problem of TCR in injection molding and most have found that it changes with time during the injection cycle [5-8]. However, in some of these studies the experimental determination of TCR was done in steady state conditions or the polymer surface temperature was not measured directly. 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 [9]. 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. [8, 10]. 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.

Results: 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 330x200x180 mm and a thickness of 2.3 mm. With such dimensions, 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 [9] and highly sensitive to temperature and inside cavity pressure changes. Shrinkage and warpage phenomena are in general quite significant for polypropylene during injection molding [8].

Figure 1 is a close up 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 SS-405C 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 acquisition for both infrared, pressure and temperature sensors were performed 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 ^{o}C or 275 ^{o}C was achieved; the mold temperature was regulated at 25 ^{o}C or 50 ^{o}C, while the hydraulic pressure during holding was set to 2.5 MPa 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 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.

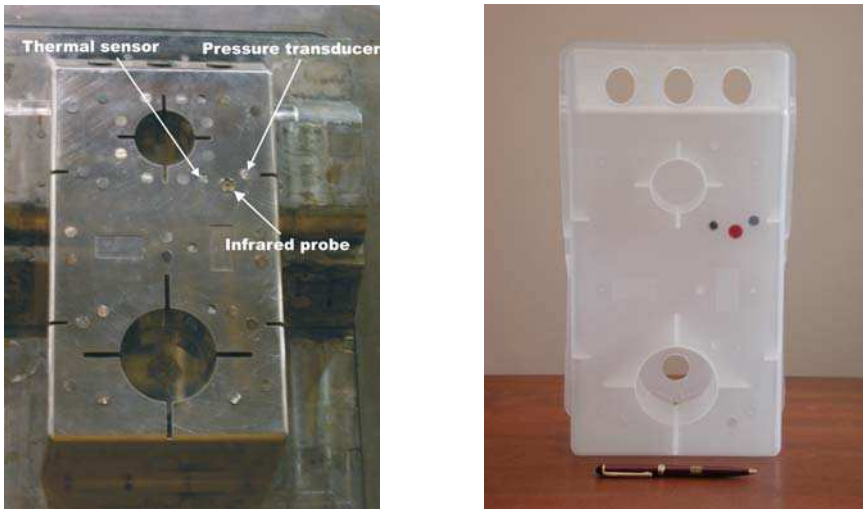

Fig. 1. Images of the mobile mold side and the polymer part showing the locations of the infrared probe, the pressure transducer, and the two-thermocouple probe.

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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. [9] 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 was devised for our needs by Miyagi's research group from Tohoku University in Japan [11, 12]. The waveguide 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 supporting 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 temperatures, 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 [13], according to Kirchhoff's law and conservation of radiant energy considerations [14], emissivity was considered to be around 97 % in the aforementioned measurement procedure.

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-thermocouple probe [10]. 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 commonly 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 thermocouples wires. Two thermocouples rather than a single one 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 $x \geq 0$) initially at temperature T_o; 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:

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

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

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

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 [15].

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 [16, 17], 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:

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

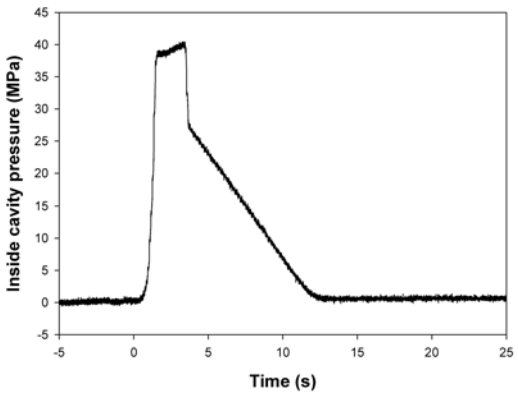
In this equation, the first subscript, j, refers to space (sensor number) and the second to time. There are r future times and J temperature sensors. $Y_{j,M+i-1}$ refers to a measured temperature by sensor number j at the time interval $[t_{M+i-2}, t_{M+i-1}]$, while $T_{j,M+i-1}$ is the exact temperature calculated by solving the forward problem, Eqs. (1) to (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:

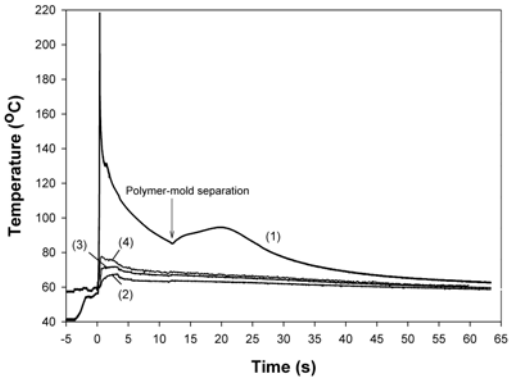
$$Z_{ji} = \sum_{k=0}^{i-1} X_{j,M+k}(t_{M+i-1}) \tag{5}$$

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 [18]. 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) to (3).





F**ig. 2. (a)** Inside cavity pressure trace recorded for an injection temperature of 220 ^{o}C, a mold temperature of 25 ^{o}C, and a hydraulic pressure of 2.5 MPa, **(b)** Measured and calculated temperature traces: (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.

In the following, we describe the experimental results obtained from validation trials. 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 thermal contact resistance. 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. Figure 2a shows a typical cavity pressure trace obtained for a mold temperature regulated at 25 ^{o}C, an injection temperature of 220 ^{o}C, and a hydraulic pressure of 2.5 MPa during holding. In the cavity, the packing/holding pressure was measured to be about 38 to 40 MPa. 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. 2b. Curve (2) refers to the 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. 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 above. The thermophysical properties of the mold material used in the inverse processing were characterized via the laser flash method [19] and a modulated differential scanning calorimeter (MDSC). The estimated values were 7800 Kg m^{-3} for the density, 29.0 W m^{-1} ^{o}C^{-1} for the thermal conductivity, and 460 J Kg^{-1} ^{o}C^{-1} for the specific heat. The mold surface temperature resulting from the inverse calculation is reported in Fig. 2b with Curve (4). On the other hand, the heat flux crossing the polymer-mold interface, also obtained from the inverse calculation, is reported via Curve (1) in Fig. 3a. TCR history that results from the measured and calculated quantities for the same molding conditions as for Fig. 2, is reported as Curve (2) in Fig. 3a. The effect of operating conditions on TCR is shown with relevant examples of TCR curves in Fig. 3b. TCR curves have been smoothed only for the sake of a clear graphical comparison analysis.

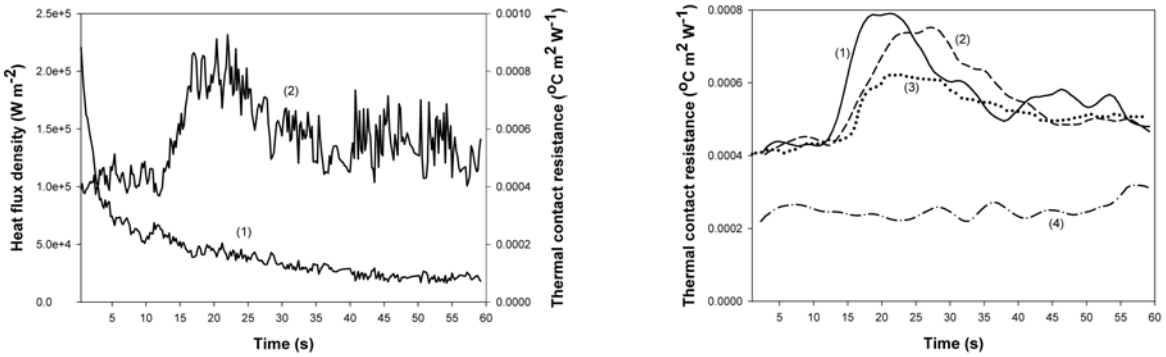


Fig. 3. (a) Surface heat flux (1) calculated using the internal temperatures provided by the two-thermocouple probe, and calculated thermal contact resistance (2), **(b)** Calculated thermal contact resistances for four different process conditions.

Discussion: From Curve (1) in Fig. 2b, we can notice that as soon as the pressure becomes equal to zero (at ~12 s, see Fig. 2a), 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. 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 seconds, 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. 2b 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.

Curve (4) in Fig. 2b, which represents the temperature at the surface of the mold cavity, shows that actually the surface temperature varies in time and increases by almost 20 ^{o}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.

The evolution in time of the heat flux density crossing the interface, Curve (1) in Fig. 3a, is typical of injection molding cycles [8, 20]. When the polymer flow front reaches the two-thermocouple probe, heat flux increases instantaneously then decreases relatively slowly as the part cools down. While Curve (2) in the same figure shows that the magnitude of TCR is in good agreement with results reported in literature [5-8]. 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 inside cavity pressure on the TCR between polymer and mold can be clearly observed by comparing Curves (1) and (2) of Fig. 3b. These curves refer to the experimental tests performed with a mold temperature of 25 ^{o}C, and an injection temperature of 220 ^{o}C. The only difference between process parameters is the hydraulic pressures used during holding (2.5 MPa and 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 ^{o}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 ^{o}C and 275 ^{o}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. 3b 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 ^{o}C and 50 ^{o}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 ^{o}C. Therefore, mold temperature is probably the most influent parameter on air gap development during injection molding.

Conclusions: 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 thermal contact resistance 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 thermal contact resistance 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-mol 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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