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Correlation between thermal contact resistance and filling behavior of a polymer melt into multiscale cavities in injection molding

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ABSTRACT

The mechanism through which thermal contact resistance (TCR) is generated and how it changes at the interface between a polymer melt and mold wall during injection molding have not yet been clearly identified. In particular, despite the TCR significantly influencing the surface quality of the resulting part, few studies have reported on the injection molding of a part with microstructural features. In this study, we predict the TCR using a new approach. Through a molding process known as "short shot", we indirectly measured the filling height of patterns as a function of time. In addition, to make these results consistent with filling analysis results, we calculated the TCR through recursive calculations. With this approach, not only changes in the TCR as a function of time but also changes by position were estimated. Furthermore, on the basis of the TCR determined in this manner, the filling behavior of micropatterns according to the change in TCR was examined. Finally, this study shows that artificial control of the roughness of a mold surface leads to control of the TCR, resulting in improved transcription of micropatterns.

1. Introduction

Thermal contact resistance (TCR) between solids has been continuously studied for the past 50 years. Surface roughness and contact pressure on the surface of contacts are factors that most strongly influence TCR. Theoretical models of TCR have also been developed [1]. In contrast, a generalized theoretical model for the TCR between a fluid and a solid—in particular, the TCR between a polymer melt and a mold used in injection molding—has not yet been established. Yu et al. [2] published the first report on TCR in this regard in 1990. Using experiments and numerical analysis, they predicted that the TCR changes depending on the injection molding conditions and time. Delaunay et al. [3] used experiments and measurements to demonstrate that during the injection molding process, the greatest change in TCR occurs when the polymer used to fill cavities shrinks and separates from the mold during the packing stage.

In contrast to the packing stage, the injection stage before packing is very short; thus, the heat flux and temperature at the interface are difficult to measure. In addition, macroscale changes are very slight; therefore, studies of TCR at this stage are rare. Nonetheless, nano/microscale structural studies of injection molding have been conducted; these studies have revealed that the influence of minute temperature changes at this interface on surface quality cannot be ignored [4].

In this study, we predict changes in the TCR according to time and position during the injection molding process (injection stage and packing stage) through experiments and numerical analyses. In particular, we investigate changes in the TCR that occur at the moment when the polymer melt contacts the mold surface and those that occur a short time thereafter. At this point, the injection molding object is a thin, rectangular plastic plate at the macroscale; at the microscale, the object's surface exhibits repeated microscale patterns. These patterns exist between the mold surface and the polymer melt; therefore, their filling behavior is directly affected by the degree of heat transfer at this interface. Thus, these patterns are expected to serve as another measure of TCR.

In polymer injection molding analysis, simulating the region where macroscale and microscale cavities coexist is difficult. Modeling and processing these cavities in a single domain is a problem that requires large memory capacity and unrealistic calculation times, which is inefficient. Thus, numerous attempts to solve this problem have been reported in the literature. Addressing this problem for the first time in 1990, Yoshii and Kuramoto [5] used a vitrified layer bending deformation model

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Nomenclature

A_1	material constant 1
A_2	material constant 2 (K)
A_{mi}	cross-sectional area of microscale inlet (m^2)
b_s	average value of the radius of the circular base (μm)
C_P	specific heat capacity (J/kg K)
D_1	material constant1 (Pa s)
D_{cc}	diameter of cooling channel (m)
e	thermal effusivity (J/m^2 K $s^{0.5}$)
F_{st}	surface tension force acting at the air/polymer melt interface (N)
g	gravity vector (m/s^2)
h	contact heat transfer coefficient (W/m^2 K)
h_c	solid contact conductance (W/m^2 K)
H_c	surface microhardness of stamper (Pa)
h_{c-c}	contact heat transfer coefficient between cooling water and core (W/m^2 K)
h_g	gas filled gap conductance (W/m^2 K)
h_{p-s}	contact heat transfer coefficient between polymer and stamper (W/m^2 K)
h_{s-c}	contact heat transfer coefficient between stamper and core (W/m^2 K)
k_{air}	thermal conductivity of air (W/m K)
k_{core}	thermal conductivity of core (W/m K)
k_{cw}	thermal conductivity of cooling water (W/m K)
k_{pm}	thermal conductivity of polymer melt (W/m K)
k_{pm}	thermal conductivity of polymer (W/m K)
k_{p-s}	harmonic mean thermal conductivity of the interface polymer melt and stamper (W/m K)
k_s	thermal conductivity of stamper (W/m K)
k_{s-c}	harmonic mean thermal conductivity of the interface stamper and core (W/m K)
M	gas parameter
$\dot{m}$	rate of mass flow (kg/s)
m	asperity slope on the front of stamper
m_{core}	asperity slope on the core
m_e	effective mean absolute asperity slope of the interface
m_s	asperity slope on the back of stamper
n	power law index in the high shear rate regime
p	pressure (Pa)
$P(\zeta)$	pressure due to the surface tension of melt (Pa)
P_0	atmospheric pressure (Pa)
P_1	pressure in the melt vicinity of the rough surface (Pa)
p_c	contact pressure (Pa)
Pr	Prandtl number
Q	heat source (J)
R	thermal contact resistance coefficient (m^2 K/W)
Re	Reynolds number
R_{p-c}	thermal contact resistance coefficient between polymer and core (m^2 K/W)
R_{p-s}	thermal contact resistance coefficient between polymer and stamper (m^2 K/W)
R_{s-c}	thermal contact resistance coefficient between stamper and core (m^2 K/W)
R_{sm}	mean peak spacing on the front of stamper (μm)
t	time (s)
T	temperature (°C)
T^*	glass transition temperature (°C)
T_0	initial air temperature (°C)
T_1	entrapped air temperature (°C)
T_{core}	temperature of core (°C)
TCR_{p-c}	thermal contact resistance between polymer and core (m^2 K/W)
TCR_{p-s}	thermal contact resistance between polymer and stamper (m^2 K/W)
TCR_{s-c}	thermal contact resistance between stamper and core (m^2 K/W)
T_{cw}	temperature of cooling water (°C)
T_{inj}	temperature of injected polymer melt (°C)
T_{mold}	temperature of mold (°C)
T_{pm}	temperature of polymer melt (°C)
T_s	temperature of stamper (°C)
u	fluid velocity (m/s)
u_m	mean velocity (m/s)
V_{f1}	volume fraction of fluid 1
V_{f2}	volume fraction of fluid 2
Y	effective gap thickness (μm)
Y_0	initial mean surface plane separation (μm)

Greek symbols

α	contact thermal accommodation parameter
β	gas property parameter
γ	mobility (m^3 s/kg)
$\dot{\gamma}$	shear rate
ε	interface thickness parameter (m)
ε	factor accounting for the gaps between the circles
ζ	surface tension of polymer melt (N/m)
η_0	zero shear viscosity (Pa s)
η_{air}	dynamic viscosity of air (Pa s)
η_{pm}	dynamic viscosity of polymer melt (Pa s)
λ	mixing energy density (N)
Λ	gas mean free path (μm)
μ_{cw}	dynamic viscosity of cooling water (Pa s)
ρ_{air}	density of air (kg/m^3)
ρ_{cw}	density of cooling water (kg/m^3)
ρ_{pm}	density of polymer melt (kg/m^3)
σ	standard deviation of the asperities heights on the front of stamper (μm)
σ_{core}	standard deviation of the asperities heights on the core (μm)
σ_e	effective RMS surface roughness (μm)
σ_s	standard deviation of the asperities heights on the back of stamper (μm)
τ^*	critical stress level at the transition to shear thinning (Pa)
ψ	phase field help variable
Φ	phase field variable

Subscripts

cc	cooling channel
$c-c$	between cooling water and core
cw	cooling water
e	effective
$f1$	fluid 1 (polymer melt)
$f2$	fluid 2 (air)
inj	injection
m	mean
mi	microscale inlet
pm	polymer melt
$p-s$	between polymer and stamper
s	stamper
$s-c$	between stamper and core
st	surface tension