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Research paper

Modeling of the thermal contact resistance time evolution at polymer–mold interface during injection molding: Effect of polymers' solidification

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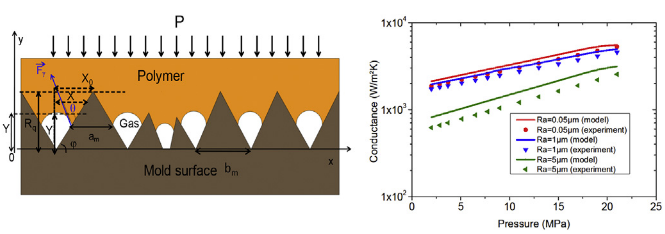
HIGHLIGHTS

- The validity of a solid–liquid thermal contact resistance model is evaluated in injection molding process.
- Crystallization is well taken into account in the predictions.
- Good agreement was found between the thermal contact resistance model and the experimental results.

GRAPHICAL ABSTRACT



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ABSTRACT

The prediction of the thermal contact resistance (TCR) evolution at polymer–mold interfaces in injection process is a key point and presents a great challenge to thermal engineers for fast simulation of the composite molding processes. In the recent studies, TCR models for rough solids contact have been modified and improved to better predict the TCR at solid–liquid interface in steady state condition varying the applied pressure or in transient condition with constant applied pressure. This study deals with the applicability of one of the existing models to predict the TCR at polymers and molds interfaces in injection process when the temperature and the pressure vary simultaneously. The model was found to be able to predict reliably the TCR even during the crystallization of the polymer at the contact interface. In addition, it has been compared with earlier experimental measurements obtained on several mold surface roughness orders, and mold surface materials. It was found to match well these earlier experimental unpublished results.

1. Introduction

Numerical simulation of heat transfer during polymers and composites materials processing is of first importance to predict the cooling time and the shrinkage after the cooling. For the professionals of the field, an accurate control of the processing of these materials requires simulations with specific software (such as Moldflow©, Cmold©, Abaqus©). In most of these software, the thermal properties of the materials are provided by a data library, or if necessary, can be measured. Moreover, to simulate the injection process, the pressure in the molding cavity and the boundary conditions of the molding process are also required. Because of the imperfect contact between the part and the mold, a thermal contact resistance (TCR) must be considered as a boundary condition in the

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Nomenclature

Aa	apparent contact area (m^2)
a_i	contact spot radius (m)
ABS	Acrylonitrile butadiene styrene
a_m	heat flux tube radius or mean contact spot radius (m)
b_m	mean asperities spacing (m)
C_p	specific heat capacity, ($J\ kg^{-1}K^{-1}$)
E	thermal effusivity ($J\ K^{-1}m^{-2}s^{-1/2}$)
F	capillarity force (N)
G	spherulites growth rate
hc	thermal conductance ($W\ m^{-2}\ K^{-1}$)
K(T)	Temperature function of the kinetics
m	mean asperities slope
n	Avrami exponent
N	number of saperities
N_0	nucleation rate
N_m	density of micro-contact spots (m^{-2})
P	pressure (Pa)
P_{appl}	apparent pressure (MPa)
P_0	atmospheric pressure (MPa)
PP	polypropylene
R	gas constant ($J\ mol^{-1}\ K^{-1}$)
R_f	interstitial resistance ($m^2\ K^{-}W^{-1}$)
R_c, r_c	constriction resistance ($m^2\ K\ W^{-1}$)
Ra	arithmetic average of the absolute values (m) of the measured profile height deviation, (m)
Rq	square root of the average of the square of the deviation of the profile from the mean line (m)
T	temperature (°C)
T_0	initial temperature (°C)
T_c	contact temperature (°C)
PTFE	polytetrafluoroethylene or teflon
TCR	Thermal contact resistance ($m^2\ K\ W^{-1}$)
$\Delta T = T_f - T$	degree of supercooling (°C)
U*	activation energy
V, *V_0*	volume of entrapped air (m^3)
x	radius of conical asperity (m)
Y	mean trapped air thickness (m)

Greek symbols

α	relative crystallinity
ρ	density ($kg\ m^{-3}$)
φ	angle between conical asperity and mean plan (°)
ϕ	Asperities height distribution
σ	standard deviation of the asperities heights, (m)
λ	thermal conductivity, ($W\ m^{-1}K^{-1}$)
λ_m	harmonic thermal conductivity ($W\ m^{-1}K^{-1}$)
θ	contact angle (°)
Ψ	constriction coefficient
γ	surface tension ($mN\ m^{-1}$) or surface energy ($mJ\ m^{-2}$)
υ	specific volume (m^3/kg)

Subscripts

s	substrate
b	bitumen
l	liquid
f	fluid

Superscripts

D	dispersive
P	polar

simulation. Indeed, in this type of problem, the cooling history is a key point since the rheology of the polymer, the final structure and the warpage depend on the evolution of the temperature field.

In an injection process, a holding pressure is applied onto the polymer, which fills the molding cavity. The large temperature gap between the hot melted polymer and the cold mold surface causes a high heat transfer. This latter one is impeded by the presence of a TCR at the polymer–mold interface. Since the injected parts are thin, the TCR is a first order parameter for the cooling, which must be known for accurate simulation. This is a tricky task since TCR evolves with time, following the main steps of the process.

The prediction of the TCR evolution at mold-polymer contact interface is a great challenge, due to the coupling between this TCR value, the temperature field and the pressure into the molding cavity. So, the boundary condition is linked to the solution of the thermal problem. This strong coupling imposes, to be able to predict the TCR evolution to solve, the thermal problem.

Study has shown that the TCR at mold-polymer interface is coupled to the thermo-mechanical behavior of the polymer [1]. Its evolution was shown to be a consequence of the shrinkage that provokes the decrease of the pressure in the mold cavity. Injection experiments [2–5] show that between the injection and the ejection of the part, the TCR at the interface changes from $2 \times 10^{-4}\ m^2\ K\ W^{-1}$ to $2 \times 10^{-3}\ m^2\ K\ W^{-1}$ due to the decrease of the pressure during the cooling. These TCR are generally obtained thanks to inverse heat transfer analysis of experimental measurements. This does not allow overcoming experiments that can be long and tedious. However, some studies [6–10] have been proposed to extend solid–solid TCR models to solid–liquid contacts, and the very recent study [11] deals with the evaluation of heat transfer coefficient estimation between polymer and mold wall in the injection molding process. A model developed in Ref. [10] was found to predict well the TCR evolution between melted bitumen and solid aggregate contact. Question has to be asked about the validity of this model to predict the TCR at amorphous or semi-crystalline polymer and mold contact interfaces. The specificities of the current study compared to the previous ones are: i) the consideration of the simultaneous evolution of the temperature and the pressure ii) the taking into account of the phase change phenomenon due to the crystallization for the semi-crystalline polymer. To achieve this objective, the predictions of the model have been compared to early experimental results [12].

The paper is organized as follows: In the first section of the paper, the early experimental results have been reminded. In the second section, the TCR model is presented. In the third part, the predictions and the earlier experimental results have been compared.

2. Earlier results

The TCR at polymers and molds interfaces has been early investigated [12]. The polymers consisted of amorphous plastic ABS (acrylonitrile butadiene styrene) and the semi-crystalline PP (polypropylene) while the mold surfaces are made with steel, teflon (PTFE) and chromium. The steel mold surface consisted of several roughness sizes. The thermal properties of the materials have been reminded in the following section.