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Modeling the injection of textured molds

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Abstract :

Micro-injection molding is frequently used in micro-medical, micro-optic and micro-mechanics due to its effectiveness for mass production. This work focuses mainly on offering numerical tools to model the injection of textured molds. Such tools can predict the different filling scenarios of the micro-details and consequently offer optimal operating conditions (mold and melt temperatures, melt flow, stresses etc.) to judge the final part quality. To do so, a fully Eulerian approach is used to model the injection of textured molds on both the macroscopic and microscopic scales. Beginning with an industrial software Rem3D, the process is modeled on the macroscopic scale where the micro details are not detected. Although the melt temperature and evolution are tracked in time, neither the micro details nor the mold temperature are properly represented. Since the thermal transfers with the mold are very relevant due to the cooling ratio, simulation on the microscopic scale are a must to insure a complete and accurate representation of textured molds injection.

Keywords : Modeling textured mold injection, Eulerian Formulation, Macroscopic scale, Microscopic scale

1 Introduction

Modeling micro-injection molding in general and textured molds injection in particular confront numerous challenges. The same physical concepts cannot be applied on both the macro and micro scale. It can be difficult to scale down the macroscopic physical properties [?]. Several factors commonly neglected in macroscopic molding simulations have significant impact on micro-injection accuracy [?] due to the greater surface-volume ratio. We cite for instance the surface tension, the surface roughness, the heating of the melt by viscous friction and the fast cooling due to the thin thickness wall [?]. In addition, the melt behavior should be inspected closely in micro-injection where more significant shear rates are involved [?]. For all the reasons mentioned above, a numerical tool modeling micro-injection is highly desirable. It helps following the flow evolution, predicting the different filling scenarios of the textured mold (especially the last filled sections) since it is unfeasible/expensive experimentally. The temperature evolution can be followed in both the melt and the mold. Heat transfers can be highlighted on the interface and in the textured zone. Numerical tools can be used as well to predict post-processing quality, based on physical notions of residual stresses and temperature for instance. No commercial software, dedicated to conventional injection molding, is able to model micro-injection processes as well. The literature classifies ongoing works to handle this problem into two categories. The first proposes developing programs specifically to model micro-injection processes. Physical phenomena are scaled down from the macroscopic scale [?]. Whereas the second adds developments to the available libraries so they can simulate micro-injection [?]. Our present work falls into the second category. We use a commercial software Rem3D [?] capable of simulating injection molding

cases. A first attempt to simulate micro-injection molding using the same library is presented herein. A multiphase Eulerian approach is adopted where the different phases are described implicitly using a Level set method [?]. The global properties are determined from local ones using mixture laws. One mesh is used all over the domain. It is anisotropically refined relocating nodes to zones where information is highly needed [?]. The adopted strategy to pass from a macroscopic to a microscopic case is described next.

2 From a macroscopic to a microscopic scale

Using the commercial software Rem3D, we model the injection molding on the macroscopic scale. The mold itself is virtual and is represented by imposing boundary conditions in both temperature and velocities. Since in micro-injection molding the thermal transfers play a key role, we propose re-modeling the case using a multiphase approach importing all the important entry data from the macroscopic software. In these multiphase simulations, the mold is no longer virtual. Heat exchanges can be examined closely. In addition, the textured cavities can be detected and different filling scenarios can be modeled.

To clarify the adopted procedure, we **first** begin by imposing the problem in the macroscopic scale. The mold cavity illustrated in Figure ?? is injected by a shear thinning material (Polypropylene) with a flow rate reaching $Q = 25 \text{ cm}^3/\text{s}$. Its inlet temperature is $T_0 = 205^\circ\text{C}$. The part exhibits micro cavities in the central zone which are not detected in the macroscopic software due to mesh limitations. The mold temperature does not vary with time and is imposed directly on the cavity boundaries, $T_m = 35^\circ\text{C}$. The melt viscosity follows Carreau-Yasuda law where the thermo-dependency is defined by a William-Landel-Ferry relation.

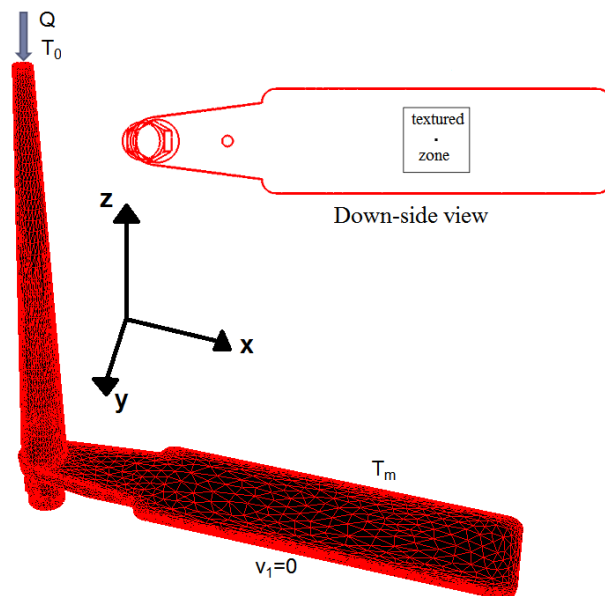


Figure 1: The cavity used in the macroscopic simulation: 50 mm by 15 mm part with a thickness of 1 mm with a textured zone beginning at 21 mm from the bottom side [?].

The evolution of the melt, the temperature and velocity are tracked in time. The melt arrives at the beginning of textured zone at $t_1 = 0.0725 \text{ s}$, at the end of this zone at $t_2 = 0.08 \text{ s}$. The cavity is filled in approximately $t_3 = 0.1 \text{ s}$. The temperature is hot in the core reaching 210°C and has cooled at the skin due to the mold temperature (35°C). The temperature and velocity plotted on a transverse section for various times are presented in Figure ?. The values of temperature and horizontal velocity remain constant in the center and are equal to 210°C and 2.5 m/s . The **second** step is to collect important data (such as temperature and velocity fields) from the macroscopic simulation to feed it to the macroscopic multiphase simulation (where the mold is properly represented). The data is collected exactly before the textured zone for maximum precision since this area will be the main focus of this study. The **last** step is to model the injection molding on the microscopic scale. The macroscopic multiphase results are fed as initial and boundary conditions.

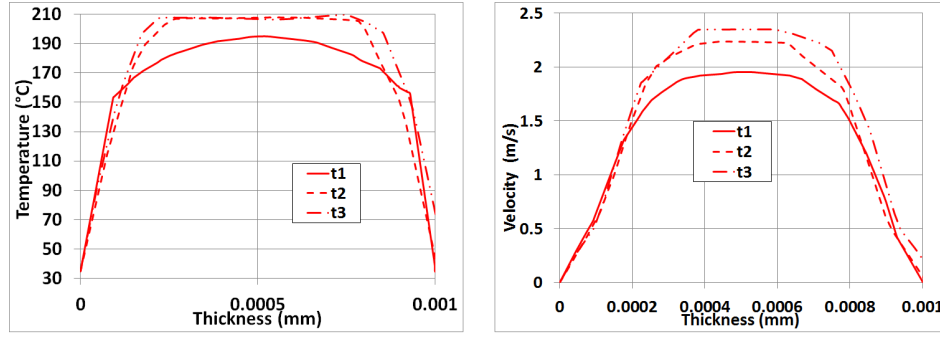


Figure 2: (a) Temperature and (b) velocity profiles in the vertical mid-line at the entrance of the textured zone for $t_1 = 0.0725 s$, $t_2 = 0.08 s$ and $t_3 = 0.1 s$.

3 Multiphase computations

The depth of the textured zone is around $10\mu m$ (or 100 times smaller than the mold thickness) and thus cannot be detected using Rem3D. The micro details are uniform slots in the transverse direction (perpendicular to the flow) on the part bottom side. This suggests that a 2D computation can be enough to draw a clear idea of the melt behavior in the textured zone. We choose a representative longitudinal section located in the center of the cavity from which all needed data are collected. They are then fed to the multiphase model as illustrated in the scheme of Figure ?? . The main parameter describing the microscopic scales is the characteristic length L_{ref} which gives the thickness of the computational domain equally divided between the mold and the cavity. In practice, we choose two characteristics lengths, L_{ref} , equal to $1 mm$ and $0.1 mm$ and boundary conditions are recovered from previous computations.

- $L_{ref} = 1 mm$ (a macroscopic multiphase computation), the flow motion corresponds roughly to a half 'Poiseuille flow'. The thermal transfers are properly represented. The upper velocity and initial temperature are deduced from Rem3D computations.
- $L_{ref} = 0.1 mm$ (a microscopic multiphase computation), the flow motion corresponds roughly to a 'Couette flow', and the cavity filling is analyzed.

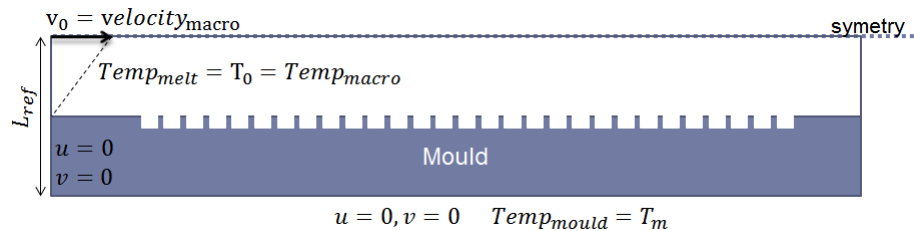


Figure 3: The 2D scheme used for microscopic modeling with $10 \times 10 \mu m^2$ micro-cavities.

It is recommended to use scaled equations in this framework. Not only zooming-in is simpler (by modifying L_{ref}) but also computing cavity filling (needing very small time steps) is possible. They enable us to work with constant fictitious time steps (namely Δt_{fict}) which corresponds to very small real time steps ($\Delta t = \Delta t_{fict} L_{ref}/V_{ref}$).

3.1 Scaled equations and no-flow criterion

The computations are performed on a rectangular domain with an unitary height. Therefore, we choose to scale the momentum and energy equations by taking L_{ref} , V_{ref} , the melt thermal conductivity k_{melt} and the reference

viscosity η_0 for scaling factors:

$$\frac{\rho V_{\text{ref}} L_{\text{ref}}}{\eta_0} (\partial_t v + v \cdot \nabla v) = \frac{\eta}{\eta_0} \Delta v - \nabla p \quad (1)$$

$$\nabla \cdot v = 0 \quad (2)$$

$$\frac{\rho C_p L_{\text{ref}} V_{\text{ref}}}{k_{\text{melt}}} \left(\frac{\partial T}{\partial t} + v \nabla T \right) - \frac{k}{k_{\text{melt}}} \Delta T = \frac{\eta_0 V_{\text{ref}}^2}{k_{\text{melt}}} \left(2 \frac{\eta}{\eta_0} \varepsilon(v) : \varepsilon(v) \right) \quad (3)$$

where v is the velocity, p the pressure, ρ the density, k the thermal conductivity, η the viscosity, T the temperature and $\varepsilon(v)$ the strain rate tensor.

Note that WLF relationship is defined all over the temperature range $[T_{\text{interface}}, T_{\text{melt}}]$. But, below a certain crystallization temperature T_c ($T_{\text{interface}} < T_c < T_{\text{melt}}$), the injected material is no longer melted and should not progress (no-flow criterion). In our approach, it is equivalent to increasing significantly the viscosity. To do so, we adjust the WLF relation by introducing an exponential function to boost the viscosity below T_c :

$$\begin{cases} \eta = \eta(T) & \text{if } T \geq T_c \\ \eta = \eta(T) e^{b(T_c - T)} & \text{if } T < T_c \end{cases} \quad (4)$$

in which $b \in [0, 1]$ is a parameter used to control properly the viscosity boost. It should be carefully chosen to reflect the closest possible results to reality.

Multiphase Computations at Macroscale: $L_{\text{ref}} = 1 \text{ mm}$

In the entrance, we impose a Poiseuille flow conserving the same flow rate ($Q = 2.5 \cdot 10^{-5} / (2 \cdot \text{width}) = 0.008333 \text{ m}^2/\text{s}$).

Thus, the reference velocity V_{ref} is equal to Q/L_{ref} . As for the temperature, a purely convective solution is imposed at the entrance and the mold temperature T_m is imposed on the lower wall.

The results are presented in Figures ???. For $y = 0$, the temperature is equal to the mold temperature 35°C . As for $y = 1$, it is equal to the melt temperature, 205°C . The interface temperature corresponding to $y = 0.5$ is equal to 47.8°C . It is in agreement with the interface temperature $\approx 47^\circ\text{C}$ calculated using the analytical formula [?].

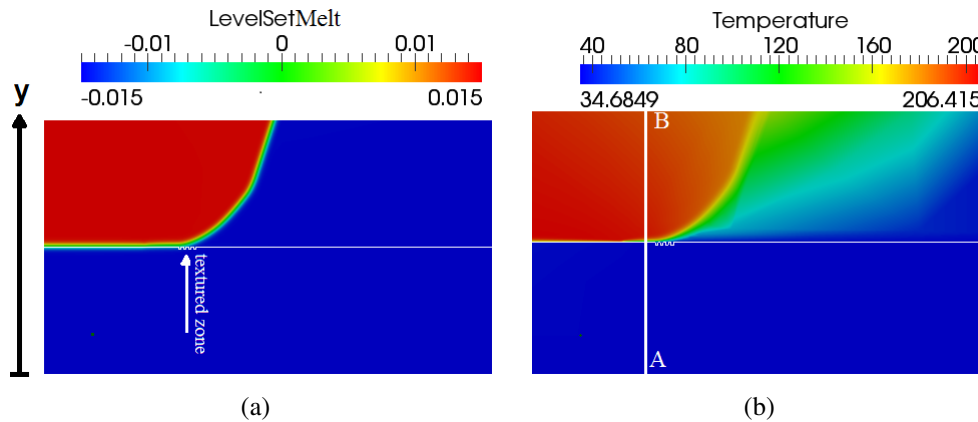


Figure 4: (a) and (b) illustrate the melt and temperature for $L_{\text{ref}} = 1 \text{ mm}$.

Studying the thermal transfers in the mold is achievable on this scale but the cavities are hardly visible. Thus, tracking the textured zone filling is impossible.

To overcome this point, we take next $L_{\text{ref}} = 0.1 \text{ mm}$ as explained earlier. This value seems suitable since the thermal boundary layer in the melt part is located for $y < 0.05 \text{ mm}$.

Multiphase Computations at Microscale: $L_{ref} = 0.1 \text{ mm}$

Taking $L_{ref} = 0.1 \text{ mm}$, it is equivalent to zooming in $1/0.1 = 10$ times. The boundary and initial conditions are recovered from the previous computation, for $L_{ref} = 1 \text{ mm}$. The melt initial velocity and temperature are respectively equal to 0.56 m/s and $205 \text{ }^\circ\text{C}$ (for $y = 0.05 \text{ mm}$ or $y = 0.55$ (normalized coordinates with $L_{ref} = 1 \text{ mm}$)). As for the new mold temperature, it is equal to $39.85 \text{ }^\circ\text{C}$ for $y = -0.05 \text{ mm}$. The microscopic case is remodeled on the smaller scale allowing better observation of both the mold and the textured zone. The no-flow criterion presented in (??) is activated by imposing $b = 1$. It increases the viscosity in the crystallization zone approximately 1000 times which is considered logic and still numerically treatable. Figures ?? (a) and (b) respectively illustrate two different filling scenarios for $b = 0$ and $b = 1$ for $t = 0.1 \text{ s}$. Identifying this parameter based purely on experimental data will be the subject of future publications.

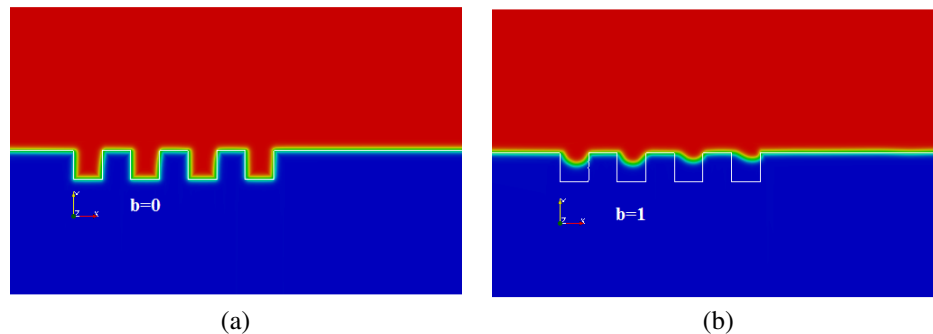


Figure 5: (a) and (b) illustrate respectively the cavities filling for $L_{ref} = 0.1 \text{ mm}$ with $b = 0$ and $b = 1$.

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