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A coupled velocity and temperature problem of the extruded spinning column in a micro-extrusion

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ABSTRACT

In this paper, we investigate a coupled velocity and temperature phase changing problem for a spinning extruded micro-column. Molten polymer is squeezed out from a spinning container in the form of a symmetrical column. The extruded and spinning fluid is being solidified through the heat exchange between the polymer in the solid state and the ambient environment resulting in a two phases (solid and liquid) problem. Temperature profile has previously been determined analytically using the boundary layer and lubrication theory techniques. However, the study on the effect of the moving boundary on the fluid flow in the liquid phase and the induced stress on the condensed shell remains absent. In this paper, we analytically deduce the velocity and stress profiles for different stages during the micro-extrusion process. Several simulations have also been performed to validate the assumptions made in the current mathematical model. We find that the velocity profile alters from certain quadratic flows into linear flows when the moving boundary retreats, and the surface stress alters from shear stress into the principal stress on the outer-shell accordingly. In conjunction with the centrifugal force induced by the spinning fluid acting on the shell, these provide some crucial factors for ensuring extruded products in their highest quality.

1. Introduction

In recent years, increasing attentions have been paid on micro manufactures. It has been found beneficial and effective to use micro-extrusion technology to produce products such as interventional catheter, micro fiber, micro gear, which are widely used in the health care, telecommunication, transportation, and other industries. In the realm of micro-extrusion, the distribution of fluid flow and temperature profile is significant in shaping the ultimate extruded products. Numerous experiments and simulations have been performed to investigate the impact of the fluid flow on the micro-extrusion [1–4]. In particular, the size effect on the micro-extrusion [5–10] and forming is also emphasized [11–15].

For instance, Yao and Kim [6] undertook the investigation of size-dependent viscosity, wall slip and surface tension on the filling procedure of polymeric materials passing through micro channels. It was found that the velocity value at the middle line of the micro channel increased dramatically as the radial dimension of the channel decreased. Chan et al. [7] investigated the size effect on the micro-extrusion process of pure copper. They found that the interfacial tension was high in the micro-extrusion and the grain size effect on the deformation load was sensitive to the friction force at the tooling workpiece interface. Lin et al. [8] investigated the frictional behavior and the flow stress in the micro-extrusion. They found that when the specimen size shrunk, the flow stress revealed a gradually downward trend and the bulging value increased while the friction factor increased. Wang et al. [9] considered the size effect on the micro backward extrusion of Zr55Cu30Al10Ni5 BMG cup-shaped specimen. In order to improve the prediction accuracy, Wang et al. [9] incorporated a size factor into the conventional component of the macroscopic formulation. Ghassemali et al. [10] studied the interactive effect of grain size and specimen dimensions on the material flow in the micro forming process, where special attention was paid on the effect of the number of grains on the evolution of the dead metal zone (DMZ) during the final stage of the micro-component's microstructure.

Apart from the size effect, material deformation was frequently investigated for micro-extrusion. For instance, Chan et al. [11] conducted an experimental and simulation study on the deformation behavior in the micro-compound extrusion process. They constructed a material constitutive model based on a

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micro-compression test and its applicability was subsequently studied. Liu et al. [12] also developed a constitutive model for predicting the deformation behavior in the microforming taking into account the grain boundary strengthen, from which the size effect on the deformation was considered. Zborowski and Canevarolo [13] devised a methodology to control a twin-screw extruder which operated as a torque rheometer to monitor the droplets deformation and recover polymer degradation during the extrusion. Li [14] also investigated the microstructure and texture evolution during the super plastic deformation of Mg-Gd-Y-Zr extruded rods. The grain structure analysis showed that during the preheating stage, the initial grain refinement was driven by the store energy inherited from the extrusion deformation. Miyazaki et al. [15] found that dislocations were evenly distributed at the grain boundaries and the deformation behavior of free surface grains was different from that of the inner region.

Majority of previous works on micro-extrusion was based on the simulations of the size effect and deformation behavior [6–15]. To the present authors' best knowledge, the interwind of the fluid flow and the moving boundary, caused by the heat exchange between solid and liquid phases, and with the ambient environment was absent in the current literature. In this paper, we initiate such investigation by considering a simple scenario, for which the extrusion completion period is short due to the extremely small extrusion scale, where the phase change effect is deemed to be dominant and its phase change period is approximately equal to the extrusion completion period. Melted polymer gradually experiences a phase change from the liquid state to the solid state resulting in the moving boundary. In this paper, we investigate the effect of the moving boundary on the fluid flow embedded inside the solidified micro-polymer. The detailed understanding of the fluidic and thermal conditions are crucial in assuring the quality of the extruded products.

2. Theory

Suppose a molten micro-polymer is squeezed into air of the temperature T_∞ to form an extruded column of radius H and length L. During the solidification, the column comprises two phases, i.e. the liquid phase is embedded inside the solid phase due to the heat exchange between both phases and with the ambient environment as described in Fig. 1, where 1 and 2 denote the liquid and solid phases, respectively. Due to the symmetry of the column, the 3D problem could be reduced to a 2D problem [16] and the final solutions could be obtained by rotating the 2D-solutions about $y = 0$. Without the loss of generality, we assume that the heat loss in the y-direction is insignificant due to the tiny temperature difference between the shell and the molten liquid, so that we could focus on the phase change occurring in the x-direction. While the heat transfer between the solid phase and the ambient environment is modeled by Newton's cooling law, the heat transfer between both the liquid and solid phases could be modeled by the latent heat resulting in the moving boundary/Stefan problem [17], where the retreat of the moving boundary is caused by the heat flux passing through the boundary, i.e.

$$\rho\lambda u_b^x = -k\frac{\partial T_s}{\partial n}\bigg|_b \tag{1}$$

where $\rho, \lambda, u_b^x, k, T_s$ and n denote the mass density of the fluid, latent heat, the velocity of the moving boundary in the x-direction, heat constant, the temperature in the solid phase and the unit normal vector pointing out of the moving boundary, respectively. It is important noting that due to the constant liquid temperature T_L, the heat fluxes arising from the liquid phase are zero at the moving boundary. To validate the assumptions given for this paper, a micro-extrusion process is simulated using ANSYS Fluent, where a molten Polyoxymethylene (POM-H) of the temperature 1273.15 K is squeezed into a column of radius $H = 10\,\mu\text{m}$ and length $L = 0.2$ mm by a velocity of 1 ms^{-1}. The temperature of the column' wall is set at 293.15 K, which is lower than the solidus temperature of the polymer, i.e. 450 K so that the solidification occurs spontaneously around the column circumstance and at the column end. The simulation result of the liquid fraction for a cross section of the column is given in Fig. 2(U). Another micro-extrusion for polypropylene (PP) with the inlet velocity 1 ms^{-1} $T_M = 600$ K, $H = 50\,\mu\text{m}$, $L = 1$ mm, $T_s = 293.15$ K, and the solidus temperature of 423.15 K is also simulated and given in Fig. 2(L) for comparison.

We observe that the solidification mostly occurs at the tube end and there exists only a very thin solid layer around the column circumstance owing to the tiny temperature difference between the shell and the molten fluid, which comes very close to the assumptions made in this paper (See Fig. 1). Sam [16] divides the temperature into six different domains and the temperature in the solid region adjacent to the moving boundary is given by

$$T_s = T_M + (T_M - T_\infty)\left\{\frac{\epsilon^{-1/2}}{L}(x - \tilde{\lambda}L) + \frac{\epsilon^{-1}}{2L^2}\left(x - \tilde{\lambda}L\right)^2 + \cdots\right\} \tag{2}$$

where ... denotes higher-order terms. In addition, $\epsilon = H/L \ll 1$ and $\tilde{\lambda} = (\rho\lambda u_b H)/[k(T_M - T_\infty)]$, where H, L, T_M, T_∞ and u_b further denotes the radius of the extruded micro-polymer, the original length of the extruded material, the melting temperature, the ambient temperature and the speed of the moving boundary, respectively. It is important noting that T_s depends only on x-direction and predicts the original location of the moving boundary as $\tilde{\lambda}L$, where $T_s = T_M$ at $x = \tilde{\lambda}L$. $\tilde{\lambda}$ is a nondimensionalised constant, which measures the balance between latent heat release from an interface moving with u_b and the conduction due to the temperature difference between T_M and T_∞. Since Eq. (2) is derived under a steady state condition, the subsequent $\tilde{\lambda}L$ is updated by $\tilde{\lambda}'L$ (see Eq. (5)) to take into account the inlet velocity and the moving boundary. The geometric

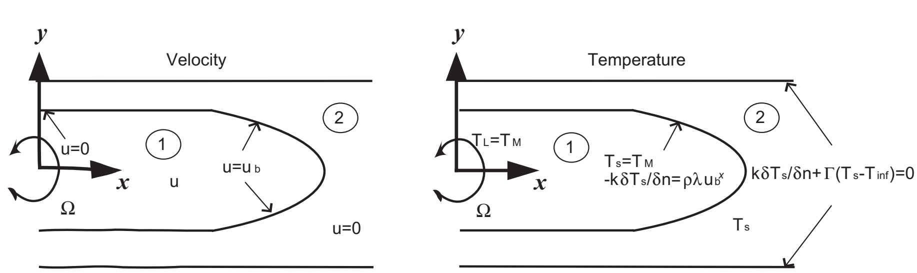

Fig. 1. Schematic diagram for the coupled problem, where $u, u_b, u_b^x, T_L, T_s, T_M, T_{inf}, \delta, k, n, \rho, \lambda$ and Γ denote the velocity of the fluid, the velocity of the moving boundary, the velocity of the moving boundary in x-direction, the temperature in the liquid phase, the temperature in the solid phase, melting temperature, room temperature, usual partial differentiation, heat constant, unit normal vector, fluid density, the latent heat and the Newton heat constant, respectively. In addition, number 1 and 2 denote the liquid and solid phases, respectively. The original problem could be restored by rotating the 2D object about $y = 0$.