Transient heat transfer and fluid dynamics during the melt spinning process of Fe$_{78}$Si$_9$B$_{12}$Mo amorphous alloy

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Abstract

A numerical model of heat transfer and fluid dynamics in the melt spinning process is developed based on the coupled Navier–Stokes and heat conduction equations. The thermal and velocity fields inside the melt puddle are calculated using the SIMPLE algorithm. The average cooling rates across the whole thickness of the puddle are characterized for different wheel velocity. The experimental investigations of thermal field and quenching rate of Fe$_{78}$Si$_9$B$_{12}$Mo amorphous alloy are conducted with the help of an infrared thermovision technique. It is shown that the calculated average cooling rate is in good agreement with experimental results over the greater part of the puddle, except for that near to the up-meniscus and down-meniscus. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Heat transfer; Flow dynamics; Melt spinning process; Amorphous alloy

1. Introduction

Of the many rapid solidification techniques currently in use, melt spinning (MS) has been studied increasingly, in particular because it could be relatively easily implemented as a large-scale industrial process. The common features of the MS operation are the transient removal of thermal energy and the high speed of fluid flow that are indeed likely to be the main factors determining the mechanical and physical properties of the solidified ribbon. While the very severe conditions in MS processes create considerable complications, numerical-modelling approaches ranging from analytical solutions to finite difference and finite element computer codes, have been used with some content of sophistication and success. Yu [1], for example, developed a low-Reynolds number planar flow melt spinning (PFMS) model based on the lubrication theory. This particular model can be used to study the effect of wheel speed and nozzle passage resistance, but it cannot take into account explicitly the heat transfer phenomena that are coupled with the fluid flow. Gutierrez and Szekely’s model [2] is also based on the lubrication theory but addresses heat transfer considerations also. This model predicts a recirculation zone inside the puddle. One of the limitations of lubrication theory, however, is that it is preferentially applicable to low Reynolds number flows, whereas the PFMS process may operate in a regime with high Reynolds numbers. Takeshita and Shingu [3] solved the momentum and energy equations simultaneously for amorphous solidification using the SOLA-VOF computer code, but heat transfer, however, was not explicitly addressed in this work. Katgerman [4] used transient momentum equations combined with a moving solidification front and solved them numerically using an explicit finite difference scheme. His model is one-dimensional, neglecting motion in the direction normal to the wheel surface. Belenkii and Olotarev [5] solved the Navier–Stokes, continuity and heat conduction equations for a two-dimensional (2D) steady state problem. They defined the dependence of the ribbon thickness on the melt temperature, wheel velocity, and heat transfer coefficient. However, the quenching rate and thermal field inside the puddle were not addressed explicitly in their work.

Direct temperature measurements have been carried in past years using both thermoelectric and pyrometric techniques [6,7]. In a few cases, cooling rates have been determined for the MS process by means of temperature-calibrated black and colour photography and cinematography. Cooling rates can also be estimated indirectly through the determination of microstructural features. Most relevant to the present study, perhaps, are some infrared thermovision and camera measurements conducted by Mathys and co-workers [8] and Pang et al. [9]. However,
the results obtained are not always agreeable and reasonable due to practical difficulties and limitations in either the forming processes or in the measuring techniques.

It appears, up to now, that a full 2D model including both the fluid flow and the heat transfer during the MS process is still unavailable. The scarcity of detailed experimental data has also impaired the development of the MS process. The purpose of this paper is to develop the numerical modelling of heat transfer and fluid dynamics in the MS process, with the ultimate objective of relating the quenching rate and fluid velocity to the operating conditions. An experimental investigation of the thermal field and quenching rate of Fe$_{70}$Si$_{5}$B$_{12}$Mo amorphous alloy is conducted with the help of an infrared thermovision technique. The characterization of the thermal and velocity fields obtained by these two approaches is also briefly discussed.

2. Process description

MS experiments were carried out in a single copper roller set at linear speeds of the wheel surface of 20–33 m/s. A schematic diagram of the MS process is shown in Fig. 1. Samples of Fe$_{70}$Si$_{5}$B$_{12}$Mo alloy were melted by an induction heater and kept in a quartz tube of internal diameter 45 mm and nozzle diameter ~1.3 mm. The nozzle is placed at a small distance from the copper wheel. The typical clearance between the nozzle and the wheel is less than 1 mm. The molten alloy was ejected through the nozzle by argon at a pressure of 0.14 MPa. The molten metal puddle under the nozzle is contained by the upstream meniscus and the downstream meniscus. The solidified ribbons were determined to be in the amorphous state by X-ray diffraction analysis. An AGA Thermovision system was employed to measure the surface temperature of the puddle versus the ribbon-wheel surface contact distance. A filtered indium antimonide detector cooled by liquid nitrogen, which was chosen for peak quantum efficiency in the 3–5.6 μm range, has a scanning rate of 25 fields per second and a thermal sensitivity of ±0.1 K at 300 K. The colour monitor is a real-time unit providing quantitative temperature.

3. Formulation

The geometry of the melt puddle is shown in Fig. 1(b). Belenkii and Olotarev [5] have shown that the length of the puddle depends on roll velocity $U_w$ and can be expressed empirically by:

$$L = 2.04 + 22.44U_w$$

(1)

It is also assumed that the parameters of the process are time independent, that there is no slip between the melt and the substrate and that the fluid flow is laminar.

The Navier–Stokes equations for 2D flow have the well-known form:

$$\frac{\partial U}{\partial t} + U \frac{\partial U}{\partial x} + V \frac{\partial U}{\partial y} = - \frac{1}{\rho} \frac{\partial P}{\partial x} + \nu(T) \nabla^2 U$$

(2a)

$$\frac{\partial V}{\partial t} + U \frac{\partial V}{\partial x} + V \frac{\partial V}{\partial y} = - \frac{1}{\rho} \frac{\partial P}{\partial y} + \nu(T) \nabla^2 V$$

(2b)

where $U$ and $V$ are the $x$- and $y$-components of velocity, respectively, $P$ is the pressure, $\rho$ is the density of the melt and $\nu(T)$ is the kinetic viscosity described by the Vogel–Fulcher–Tammann equation [5].

$$\nu(T) = \frac{A}{\rho} \exp \left( \frac{B}{T - C} \right)$$

(3)

The continuity equation is written as:

$$\frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} = 0$$

(4)

The initial and boundary conditions for the solution of $U(x,y)$, $V(x,y)$ and $P(x,y)$ are written as:

$$U = U_i, \quad V = V_i, \quad P = \int_0^y \rho g dy$$

(5a)

for $0 \leq x \leq L, \quad 0 \leq y \leq H$ at $t = 0$

$$\frac{\partial U}{\partial x} = 0, \quad \frac{\partial V}{\partial x} = 0, \quad \frac{\partial P}{\partial x} = 0, \quad \text{at } x = 0 \text{ and } x = L$$

(5b)

$$U = U_w, \quad V = 0, \quad \frac{\partial P}{\partial y} = 0 \quad \text{at } y = 0$$

(5c)

Fig. 1. Schematic of: (a) the melt spinning set; and (b) the calculated domain of the melt puddle.
\[ U = 0, \ V = V_j, \quad \frac{\partial P}{\partial y} = 0 \quad \text{at} \ y = H \quad \text{for} \quad 0 \leq x \leq L_1 \quad (5d) \]

\[ U = 0, \ V = 0, \quad \frac{\partial P}{\partial y} = 0 \quad \text{at} \ y = H \quad \text{for} \quad L_1 \leq x \leq L \quad (5e) \]

The governing heat conduction equation is:
\[
\frac{\partial T}{\partial t} + U \frac{\partial T}{\partial x} + V \frac{\partial T}{\partial y} = \alpha \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) \quad (6)
\]

where \( \alpha \) is the thermal diffusivity, \( k \rho C_p \) (\( k \) is the thermal conductivity and \( C_p \) the heat capacity).

On the wheel surface, the heat transfer condition is:
\[
K \frac{\partial T}{\partial y} \bigg|_{y=0} = h_i(T - T_w) \quad (7)
\]

where \( T_w \) is the wheel surface temperature and \( h_i \) is the heat transfer coefficient between the wheel and the melt. At the back boundary, \( x = 0 \) and at the top of the puddle, \( y = H \), the condition \( T = T_0 \) holds, \( T_0 \) being the melt temperature. At the downstream meniscus, \( x = L \), the condition \( \partial T / \partial x = 0 \) holds.

Eqs. (1)–(7), together with the above boundary conditions, represent a complete statement of the problem. The parameters and properties used in the calculation are obtained from Refs. [2,5]. The numerical method used in this paper is similar to the SIMPLE algorithm developed by Patankar [10]. In order to avoid oscillation of the algorithm, the velocity, pressure and temperature values were calculated at different points of the control volumes. The procedure for the calculation is as follows: (1) the first guess for velocities \( U \) and \( V \) at a new time level is evaluated from the explicit approximation of the momentum equations using \( U \), \( V \) and \( P \) at an old time level; (2) to satisfy the continuity equation, pressures are iteratively adjusted in each cell occupied using the Guss–Ziedel algorithm. After that, inside the same iterative loop, the temperature and viscosity are calculated. Thus, the change in the temperature field induces a suitable change of the viscosity, which, in turn, influences the velocity field during the next iteration. The convergence by means of the square difference of pressures is tested and the cycles are repeated.

4. Results and discussion

4.1. Fluid flow field

Fig. 2 shows the predicted final velocity fields inside the melt puddle of Fe–Si–B–Mo alloy for \( U_w = 20 \) m/s.
$V_j = 5$ m/s. Just as the authors expected, the majority of the fluid flow in the $y$ direction takes place at the left-upper portion near to the nozzle. It is worth noting that there are sharp variations in the $y$-component of velocities at the location where the distance from the up-menisicus is equal to the width of the nozzle. Upon inspection of the $x$-component velocity field, it is found, surprisingly, that the maximum flow does not occur close to the wheel surface but at the mid-height portion under the nozzle. This particular fluid flow pattern is perhaps caused by the interaction between the dragging force of the wheel surface and the ejecting pressure at the nozzle. Another noticeable feature of the computed flow field is that there is no recirculation zone seen in the puddle. Such a region was predicted by a model using the lubrication theory analysis [1,2]. It is not clear at this point what causes this difference. On the other hand, the Navier–Stokes equation, which is unlike the lubrication equation, does include an inertial term, which could be predominant because of the high Reynolds number involved. Some work conducted with the Navier–Stokes equations did show a recirculation zone for PFMS under certain conditions [3], but this model did not include heat transfer and solidification in the puddle, and cannot therefore be directly compared with the present model. The model has been recently improved by developing an explicit–implicit scheme, and by expanding the system of equations to the full Navier–Stokes level. When fully operational, this new model should give a better understanding of the flow fields.

4.2. Thermal field and cooling rate

The calculated thermal field and the iso-thermal contour inside the puddle of Fe–Si–B alloy are shown in Fig. 3. It is seen clearly that the isotherms lie almost parallel to the wheel surface throughout most of the puddle and that the temperature change takes place within a relatively narrow area close to the wheel. The temperature in the upper half of the puddle is very close to the initial value. Furthermore, freezing does not start immediately at the point of impingement of the molten jet on the wheel because of the use of the heat transfer coefficient at the melt–wheel interface.

The average cooling rates for various wheel velocities as a function of the distance from the up-menisicus are shown in Fig. 4. It is seen that the average cooling rate is about $4 \times 10^5$ K/s in the initial stage of the puddle. The cooling rate then decreases sharply as distance from the up-menisicus increases. It reaches a minimum at the value of $x$-coordinate equal to the width of the nozzle. This minimum cooling rate coincides with the minimum temperature gradient at the same location, as shown in Fig. 3(b). As the distance increases further, the cooling rate then increases again. The variations of the cooling rate at the second half part of the puddle are different for various wheel velocities. It is seen that the cooling rate for $U_w = 20$ m/s, first rises gradually and then increases sharply as the down stream meniscus is approached. The cooling rates for $U_w = 5$ and $U_w = 10$ m/s, however, decrease slightly from $x = 1.2$ to $x = 2.5$ mm, but finally increase remarkably. In view of
the overall average cooling rates throughout the whole domain, it is shown that the larger is the wheel velocity, the higher is the average cooling rate. The influence of the wheel velocity on the average cooling rate near to the downstream meniscus of the puddle is larger than that at the initial part. This result suggests that increasing wheel velocity could be beneficial to the achievement of amorphous microstructure.

A 2D AGA thermovision photograph of the Fe$_70$Si$_{12}$Mo amorphous alloy with a wheel speed 33 m/s is shown in Fig. 5. Fifteen selective colours provide quantitative thermal images relevant to different temperatures. Fig. 6 shows the plots of experimental and calculated cooling rate versus the ribbon–wheel contact surface distance from the back boundary for the alloy with $U_w = 33$ m/s. It is seen that the calculated result is in good agreement with the experimental values over the greater part of the puddle. Both of the plots have a minimum value of cooling rate at $x = 1$ mm. The calculated values near to the back boundary and the downstream meniscus are considerably larger than the measured results. An obvious hump is seen at the experimental plot for $x = 1.5$ mm, but the hump at the calculated plot is very small. This situation may be the result of the estimated heat transfer coefficient between the melt puddle and the wheel. The heat transfer coefficient is one of the major parameters controlling the MS process, and is therefore also a critical boundary condition for the numerical model. It probably depends on the condition of the wheel, the types of the melt, the level of gas entrainment, the ambient and local pressure etc. There is apparently no general model available at the present time that can predict accurately the value of this coefficient for various operational conditions. In this calculation, the authors used an average heat transfer coefficient for the whole puddle. It is possible that the values of the heat transfer coefficient near to the back boundary and downstream meniscus are much lower than the average level. Therefore the calculated cooling rates at these two portions are much higher than those obtained in practical measurements.

5. Conclusions

1. A 2D numerical modelling of heat transfer and fluid dynamics in the MS process has been developed based on the coupled momentum, mass continuity and heat conduction equations. A numerical scheme similar to the SIMPLE algorithm was used to solve the thermal and velocity fields.

2. The majority of the fluid flow in the direction normal to the wheel surface takes place at the left-upper portion near to the nozzle. There are sharp variations in the fluid flow along the y-direction at the location where the distance from the up-meniscus is equal to the width of the nozzle. The maximum flow in the $x$-direction does not occur close to the wheel surface but at the portion of mid-height under the nozzle. No recirculation zone in the melt puddle is predicted by this model.

3. The isotherms lie almost parallel to the wheel surface throughout most of the puddle and the temperature change takes place within a relatively narrow area close to the wheel. The average cooling rate decreases sharply as solidification sets in, and reaches a minimum near to the location where the value of the $x$-coordinate is equal to the width of the nozzle. The larger is the wheel velocity, the higher is the average cooling rate.

4. The present experimental investigation of the solidification puddle was carried out with the help of an infrared thermovision technique, which enabled the thermal field and cooling rate inside the melt puddle to be obtained.
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