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Cooling wheel features and amorphous ribbon formation during planar flow melt spinning process

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ABSTRACT

A numerical model incorporating actual production conditions of planar flow melt spinning process is presented. Knowledge of the process conditions at which an amorphous ribbon with uniform thickness can be obtained is important to reduce the manufacturing costs. Cooling wheel conditions play a significant role during rapid solidification of the melt. Hence a heat transfer analysis is performed to investigate the influence of cooling wheel temperature on ribbon formation. Nusselt's correlation is used for the first time for selecting a convective heat transfer coefficient between rotating wheel and surrounding air. This approach assists in predicting the conditions at which a continuous/broken/no ribbon formation is obtained during the process. The model could predict whether the ribbon to be obtained is amorphous or non-amorphous before the experiment is actually performed at a set of process conditions. Various internal and external conditions of the cooling wheel are tested, and they show little influence on the ribbon thickness up to 0.5 s (10 rotations). Broken and nonamorphous ribbons are obtained for poor cooling conditions of the wheel with increase in time of cast from 0.5 s to 1 s (20 rotations). Amorphous ribbon with uniform thickness can be obtained for a wheel of 20 mm wall thickness, when the inner and outer surfaces of the cooling wheel are maintained at a temperature of at least 300 K.

1. Introduction

Distribution transformers with amorphous ribbon core reduce the core losses to about 70–75%. Narasimhan and Flanders (1979) invented planar flow melt spinning (PFMS) process to produce amorphous ribbons by rapid solidification of molten alloy. Molten metal comes out of the crucible through a slit nozzle by applying inert gas pressure on the surface. Melt accumulates in the form of a pool or puddle between nozzle walls and rotating copper wheel. A thin layer of melt is dragged out of the puddle in the form of a ribbon due to cooling wheel rotation. The process is shown schematically in Fig. 1(a) and puddle with ribbon formation in Fig. 1(b).

Rapid solidification with a high cooling rate ($10^6\,^{\circ}$C/s) is essential for a ribbon to be amorphous. This is obtained by heat abstraction at high rates by the copper wheel from the melt puddle. The heat in turn is being taken away by the cooling water in the rotating copper wheel and by the surrounding atmospheric air due to wheel rotation. Nonamorphous ribbons obtained during experiments (Fig. 1(c) and (d)) motivated to investigate the heat transfer process from the melt to the cooling wheel. As the process involves rapid cooling of the melt, experimental investigation of influence of heat transfer at the melt wheel contact on amorphous ribbon formation is difficult. Hence numerical simulation is used to understand the heat transfer mechanism taking place during PFMS process.

Many investigators replaced wheel as a boundary with constant wall temperature or with single value heat transfer coefficient (h, W/m^2 K) as a simplification in the numerical heat transfer models. Convective heat transfer coefficient 'h' is the proportionality constant between the heat flux and the temperature difference between the melt and wheel. As heat flux is constant during an experiment 'h' is inversely proportional to the temperature difference between the melt and the wheel. High value of 'h' is essential during rapid solidification process to obtain a cooling rate of $10^6\,^{\circ}$C/s.

Takeshita and Shingu (1986) estimated the 'h' values at the melt-wheel contact as 7×10^5 W/m^2 K to 1.3×10^6 W/m^2 K by measuring the temperature of the solidified ribbon by IR thermometer. The 'h' value after change is estimated to be constant at 2×10^5 W/m^2 K. Wu et al. (1992) developed a 2-D model with transient fluid flow and heat transfer in PFMS process. A constant

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Nomenclature

w	nozzle slit width
F	volume fraction
G	nozzle-wheel gap
P	pressure
ω_d	wheel speed
t	ribbon thickness
T_{ej}	ejection temperature
T_g	glass transition temperature
h_{in}	internal surface heat transfer coefficient
h_{out}, h'_{out}	external surface heat transfer coefficient
Nu_D	Nusselt number based on wheel diameter
Re_w	Reynolds number based on wheel speed
Gr_D	Grashoff number based on wheel diameter
Q1	convective heat transfer at USM
Q3	heat flow in the ribbon
Q_w	heat flow to wheel
Pr	Prandtl number
g	gravitational acceleration
u, v	x, y direction velocities
R	wheel radius
D	wheel diameter
Δt	difference in ribbon thickness
b	wheel wall thickness
T_w	internal wall temperature
k	thermal conductivity
M.P.	melting point
ρ	density
C_p	specific heat
μ	dynamic viscosity
Q2	heat flow at DSM
Q_{in}	heat flow at inlet

heat transfer coefficient 10^5 W/m^2 K was assumed at the melt substrate interface. Carpenter and Steen (1997) by a numerical model found that the ribbon thickness is being limited greatly by the flow parameters and not exclusively by interface growth in the melt puddle. Bussmann et al. (2002) observed a stable puddle formation in 10 ms, assumed a constant '*h*' at the wheel surface and predicted changes in the temperature in the melt puddle for Ni–B alloy system. Wang and Matthys (2002a,b) experimentally investigated for the interfacial heat transfer coefficient for Nickel splats on different substrates. The results show the '*h*' value can be as high as 3×10^5 W/m^2 K when the molten metal is in contact with the substrate. Wang and Matthys (2002a,b) developed a mathematical model to simulate the heat transfer and non equilibrium solidification in the PFMS process for Al Alloy and assumed a constant 'h' as 10^6 W/m^2 K. Sundararajan and Thomas (2008) analyzed heat transfer during melt spinning process. A 2D model was considered with a portion of the wheel of 12.7 mm casing thickness under the puddle. The wheel casing was assumed as flat and was divided into three zones of (i) under the puddle, (ii) ribbon contact zone and (iii) ribbon detached zone. The model was extended to 3D to observe transverse surface depressions. The influence of wheel expansion due to heat up was observed to cause depressions in the ribbon on wheel side. Liu et al. (2009) observed a study puddle by 10 ms using a model developed by commercial CFD software. Karpe et al. (2009) observed in their mathematical model that for wheel thickness of 10 mm, heat removal rate from the melt would be slower which leads to increase in wheel temperatures and thermal stresses were observed to be a limiting factor for wheels of very low casing thickness (<10 mm). Theisen et al. (2010) found experimentally that the solidification rate decreases with time and also observed wheel heat up during cast in his analytical model. Liu et al. (2010) performed a thermal deformation analysis of the cooling wheel and observed that for a small puddle length over very short ribbon formation time, variation in the deformation of the roller was small.

Karpe et al. (2011) investigated the influence of different chill wheel materials on the heat contact resistance between puddle and wheel. Cu-Be or ODS copper alloy were suggested for better heat transfer from the melt to wheel. Karpe et al. (2012) restricted the reduction in wall thickness to 2 mm as thermal resistance becomes a limiting factor on the cooling side of the wheel. Present authors (Majumdar et al., 2012; Sowjanya et al., 2013) studied the puddle formation by a 2-D model at various process conditions and ribbon topography by a 3-D model at various melt ejection temperatures. Wheel surface was assumed at constant temperature of 300 K in both the studies. With this assumption a heat transfer coefficient 10^6 W/m^2 K was obtained between melt and the wall boundary. A stable puddle was observed by 10 ms after melt ejection, of which ribbon of uniform thickness can be obtained.

All the above models used a high value of heat transfer coefficient or constant wall boundary at the melt wheel contact to get amorphous ribbon. But the ribbons obtained during experiments with PFMS equipment often resulted as nonamorphous. Hence the present numerical simulation is focused on the conditions at which amorphous ribbon of uniform thickness can be obtained. In the present study, domain is extended on both sides of the nozzle walls to observe the heat dissipation from the melt puddle to the surrounding air. Wall boundary at the melt wheel contact is replaced by a rotating copper wheel with 20 mm wall thickness. Entire wheel is included in the computational domain unlike the model of Sundararajan and Thomas (2008). A coupled wall between air and wheel domains at the melt-wheel contact allows the heat transfer between melt and wheel. Liu et al. (2009) assumed an approximate value of heat transfer coefficient between air and rotating wheel surface. Energy and flow equations were decoupled in every rotation of the wheel as soon as it leaves the puddle zone. Viscosity was taken as temperature dependent and assumed as 1 at and below the glass transition temperature of the alloy (873 K). In the present model a convective heat transfer coefficient is introduced for the first time based on the Nusselt's correlation for heat transfer between the rotating wheel outer surface and the surrounding air. Energy and flow equations are coupled always in the entire simulation to be more realistic to the practical situations. Viscosity is calculated up to 500 °C and assumed as constant at the same value at lower temperatures.

2. Numerical model

A 2-D, time dependent numerical model is used with two domains (fluid and solid) to simulate heat transfer during the PFMS process. Space between flat nozzle bottom extending on both sides of the walls and copper wheel is modeled as a fluid domain. Hollow copper wheel with 20 mm wall thickness is modeled as a solid domain. Volume of fluid (VOF) method is employed in the air domain with geometric reconstruction scheme to track the moving interface. Unstructured quad mesh with 0.9 quality is achieved in both the domains. Fig. 2(a) shows the geometry of air domain on the copper wheel. Crucible with nozzle is replaced by melt inlet to the air domain at CD and nozzle walls as BC and DE. Surrounding atmosphere is represented by AB, AG, EF and FH. Wall GH is a coupled wall between the fluid (air) and solid (wheel) domains which allow the heat transfer from the molten metal into the copper wheel. Outer surface of the wheel other than coupled wall is a boundary exposed to surrounding air and inner surface is exposed to water. Dense mesh is developed below the melt inlet and below the nozzle in air and solid domains as shown in Fig. 2(b). Coarse