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Transient behavior of the planar-flow melt spinning process

E.A. Theisen [a,*,1], M.J. Davis [b], S.J. Weinstein [c], P.H. Steen [d]

[a] Metglas Inc., 440 Allied Dr, Conway, SC 29526, USA
[b] Engineering Sciences and Applied Mathematics, Northwestern University, Evanston, IL 60208-3125, USA
[c] Department of Chemical and Biomedical Engineering, Rochester Institute of Technology, Rochester, NY 14623, USA
[d] School of Chemical and Biomolecular Engineering, Cornell University, Ithaca, NY 14853, USA

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ABSTRACT

Planar-flow melt spinning (PFMS) is a single-stage rapid manufacturing technique for producing thin metal sheets or ribbons. Commercial acceptance of PFMS requires ribbons to be cast with uniform thickness to tolerance. The process feeds molten metal through a nozzle onto a moving wheel where a puddle is formed and from which a continuous ribbon is 'spun'. This study focuses on the time dependent behavior of the process. The dynamics of the process are modeled using unsteady mass balances, combined with a Bernoulli model of flow. Variations over a number of time scales are observed. The time scale over which the process can be treated as 'quasi-steady' is identified. Measuring the evolution of the puddle length and ribbon thickness within a cast indicates that the solidification rate also varies with time and a maximum in solidification rate is inferred.

1. Introduction

Planar-flow melt spinning (PFMS) is a continuous casting method for producing rapidly solidified thin sheets or ribbons of metal. The industrial motivation for PFMS comes from the novel properties of the ribbon, as well as the cost savings of processing in a single stage (Narasimhan, 1979; Pimputkar et al., 1985). PFMS is the most commonly used process for producing amorphous soft magnetic ribbons which are used in high efficiency energy conversion devices such as utility transformers (Hasegawa, 2004). The ribbon thickness is the main output variable for the process and maintaining a constant thickness is desirable for commercialization of the PFMS process. The material properties of the ribbon depend in large part on the rate at which the ribbon solidifies (Barth et al., 1997; Karaaslan et al., 1998). Many studies have focused on relating the processing parameters to the steady-state behavior of the process (Praisner et al., 1995; Fiedler et al., 1984). However, there have been few studies that focus on the time-dependent behavior of PFMS. Our goal is to develop a fundamental understanding of the ribbon thickness and solidification rate variations that occur within a cast so that they can be predicted and ultimately controlled.

The key feature of PFMS is that molten metal is fed through a nozzle and impinges on a rotating chill-wheel. The narrow spacing between the nozzle face and the wheel causes a puddle to form in the gap, as shown in Fig. 1. Upon contacting, the molten metal rapidly solidifies and a continuous ribbon is removed from the puddle. Controlling the flow of molten metal through the nozzle and the solidification rate are critical to maintaining a uniform ribbon thickness with desired material properties (Das et al., 1997). The interaction between fluid flow, heat transfer, and the solidification that occurs within the puddle is an area of active research (Napolitano and Meco, 2004; Liu et al., 2009).

Much of the work in PFMS has focused on the high cooling rates, on the order of 10^4–10^7 C/s, which can result in amorphous metals (Kavesh, 1978; Jones, 1982). The morphology of the ribbon is strongly dependent on the time, τ_s, in which the ribbon solidifies, as given by the ratio of the puddle length, L, and the wheel speed, U ($\tau_s = L/U$). For a given τ_s, the ribbon thickness, T, depends mainly upon the heat transfer from the molten metal puddle to the wheel. The location of the solidification front within the puddle depends upon many factors, including (but is not limited to) the wheel and molten metal temperatures, the wheel surface roughness, the thermophysical properties of the wheel and the contacting between the molten metal and the wheel (Wang and Matthys, 2002). Perfect contact is never truly achieved and a heat transfer coefficient is commonly used in models which couple the solidification rate to measurements of T and τ_s (Muhlbach et al., 1987; Vogt, 1987).

The steady fluid flow within the puddle can often be treated separately from the heat transfer. It has been found that for long liquid puddles, the energy equation decouples from the momentum equation, allowing for heat transfer to be analyzed independently

* Corresponding author.
E-mail address: Eric.Theisen@metglas.com (E.A. Theisen).
[1] Work largely done at Cornell University.

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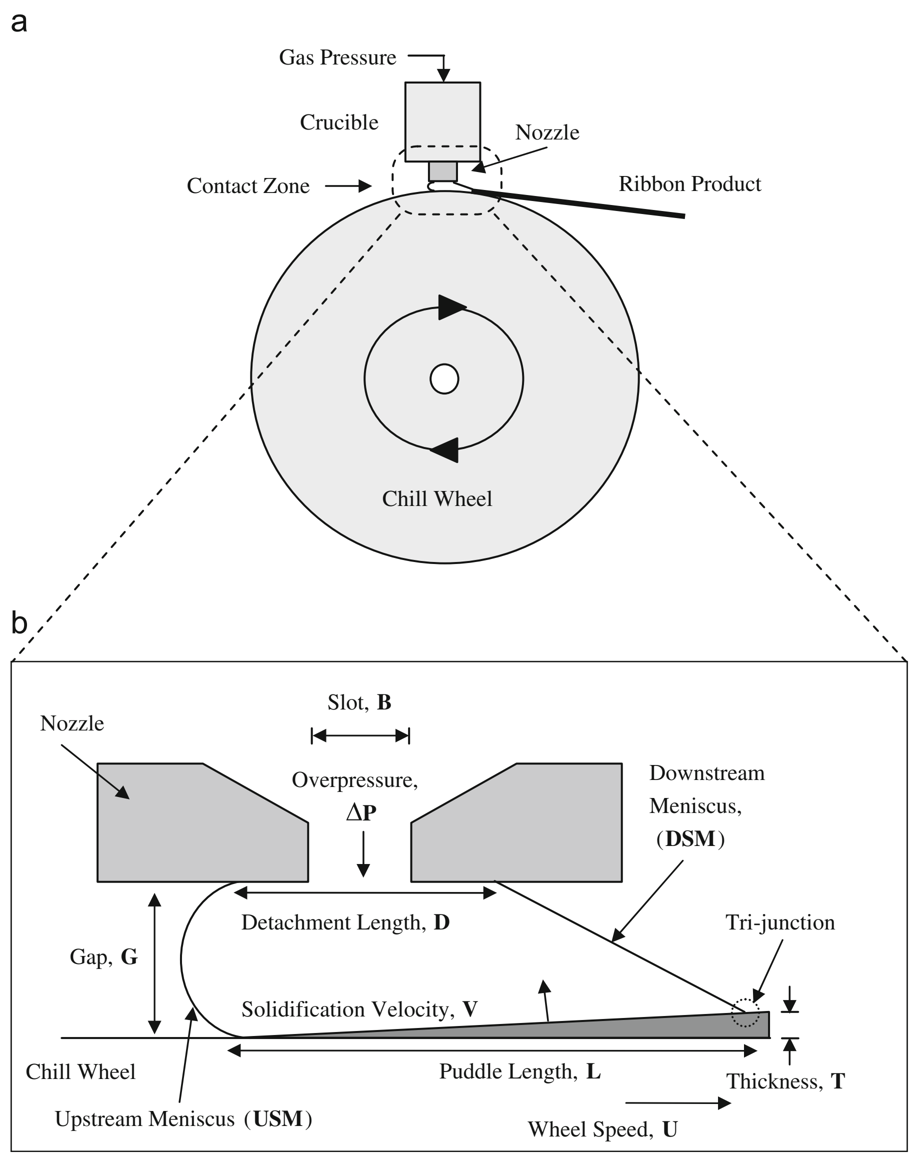

Fig. 1. (a) Schematic of the PFMS apparatus. Molten metal flows from the crucible through a nozzle onto the spinning substrate or chill-wheel, where it forms a puddle. Solidification occurs and a continuous ribbon is 'spun' from the puddle and released from the substrate. (b) Blow-up of the contact zone or puddle region. Note that the horizontal length scale has been compressed for clarity.

from the fluid dynamics of the process (Carpenter and Steen, 1997). The steady flow in the puddle region is predominantly inviscid and can be modeled analytically by combining mass and Bernoulli balances (Huang, 1981; Sung et al., 1994; Tkatch et al., 2002). Steen and Karcher (1997) provide a review of the fluid mechanics of the PFMS process and Bussmann et al. (2002) provide a recent review of the numerical approaches used to quantify the steady flow and temperature fields within the puddle.

The range of length scales relevant to PFMS processing on our experimental caster are illustrated in Fig. 2. Time scales correspond through U. Casting a ribbon of uniform material properties and thickness is challenging due to the disparity of length scales associated with the process. We find that T often decreases over the entire cast length with superposed variations on the scale of wheel circumference. Smaller scale macroscopic T variations occur periodically (mm or cm wavelength), as surface defects on the ribbon (Praisner et al., 1995; Haga and Suzuki, 2003). These periodic defects were the focus of previous studies and are related to capillary vibrations of the puddle (Napolitano and Meco, 2004; Byrne et al., 2006a). At yet a smaller scale, the surface roughness of the ribbon can influence its physical properties. That is, surface features can dominate bulk properties of thin film material. The ribbon surface roughness is also related to many of the magnetic properties of metallic glasses. For example, the electrical losses of a transformer depend strongly on the surface morphology of the ribbon within the core (Gyorgy, 1978). On the smallest scale, variations in the solidification rate have been related to the microstructural features (μm) of the ribbon (Byrne et al., 2007). In the current study we focus on T variations on the longer length scales of the wheel circumference (m) and the entire cast length (10^2 m).

Fig. 3 shows how T and puddle length L evolve over τ_{cast}, the time of the cast length. There is a steady decrease in T through the cast with a shorter scale periodic variation. The periodic variation occurs over the time scale of the wheel revolution, $\tau_{rev} = C_w/U$, where C_w is the circumference of the wheel. A moving average of one wheel circumference is added to indicate how T deviates from a 'steady' value during each wheel revolution. These T variations correspond to a time-dependent behavior in the gap spacing, G, between the nozzle and the wheel. The wheel expands thermally