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Materials Science and Engineering A 459 (2007) 172–181

MATERIALS SCIENCE & ENGINEERING A

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# In situ manipulation of cooling rates during planar-flow melt spinning processing

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Received 8 September 2006; received in revised form 20 December 2006; accepted 21 December 2006

**Abstract**

Planar-flow melt spinning (PFMS) is a single stage rapid manufacturing/solidification technique for producing thin metallic sheet or foil. A new technology, envisioned to allow real-time manipulation of the local cooling rates and properties in melt-spun ribbon, has been tested successfully when casting Al–7%Si. Pulsed laser heating, directed low on the upstream meniscus, or on the substrate, leaves patterns of 'dimples' in the ribbon. Typical cooling rates of $10^4$ K/s have been measured using a control-volume approach. Secondary dendrite arm spacing (SDAS) has been measured through the thickness of ribbons showing areas both affected by the laser heating and unaffected by the laser. Through a correlation of cooling rates and SDAS, it is shown that the unmodified ribbon has an average cooling rate similar to that measured macroscopically. The cooling rate underneath a laser dimple is estimated to be six times slower near the contact surface. It is envisioned that the technology described may bring the concept of 'casting-by-design' one step closer to realization.


*Keywords:* Spin casting; Metal casting; Materials Processing; Secondary dendrite arm spacing; Cooling rates; Laser

## 1. Introduction

Every year in the United States, over 2 billion pounds of aluminum sheet and foil is produced [1]. Casting and rolling mills use tens of millions of dollars worth of electricity every year to power the rollers and heaters used in the multi-step production processes [2]. It is estimated that single-step processing (i.e., straight from the melt to the finished aluminum product) could significantly lower energy requirements and in addition, could reduce $CO_2$ emissions in the US by up to 250,000 tonnes per year [3]. Planar-flow melt spinning (PFMS), also known as planar-flow spin casting, is a process that can potentially provide this faster and less energy-intensive processing of thin metal sheet and foil products. The process was first introduced in the 1970s [4]. Most interest has come from the materials science community, due to the unique microstructural characteristics obtained from cooling rates ranging from $10^4$ to $10^8$ K/s [5]. Our work has been focused on the processing aspects and though we use aluminum alloys, we are not limited by alloy type.

In the PFMS process, molten metal is allowed to flow through a planar nozzle which is in close proximity to a rotating metallic wheel or substrate (see Fig. 1). A liquid metal puddle, constrained by surface tension, is formed between the nozzle and substrate. Molten metal is a Newtonian liquid. Heat is rapidly transferred from the molten metal to the cooler substrate as it rotates underneath the puddle. A solid metal front grows from the substrate surface, with an average velocity $V$, as it translates through the puddle region. Eventually, a ribbon emerges from the puddle and is thrown from the substrate. For a fixed nozzle geometry, the thickness of the ribbon $T$, depends on several parameters including the wheel speed $U \sim 10\,\mathrm{ms}^{-1}$, the nozzle-to-substrate gap distance $G \sim 1$ mm, and the pressure of the liquid metal as it exits the nozzle $\Delta P \sim 4000$ Pa. In general, $\Delta P/\rho U^2 \sim T/G^2$. A review of the general stability and fluid dynamics of the process is available [6].

The development of a truly single stage continuous casting technology requires an ability to control the geometry and properties of the metal during the solidification event to avoid further downstream processing steps. Such control extends over a variety of length scales, from the overall product length (meters)

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doi:10.1016/j.msea.2006.12.123

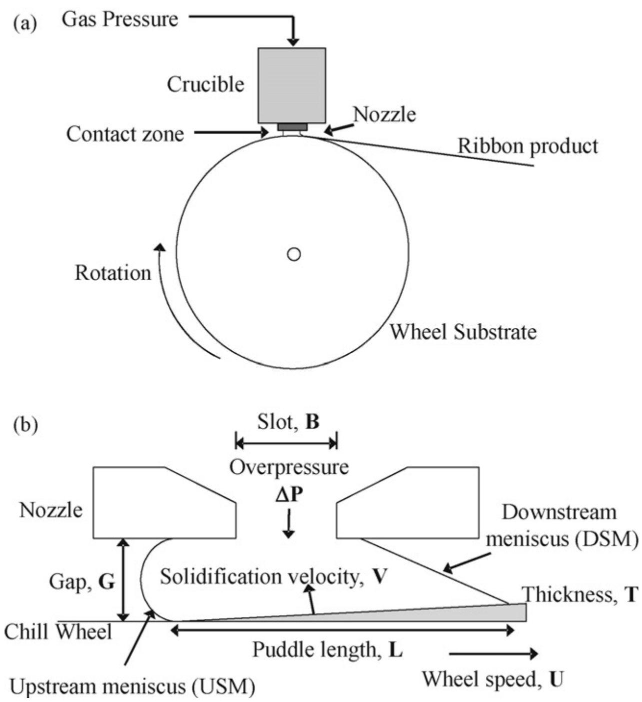


Fig. 1. (a) Schematic of melt spinning apparatus and (b) enlarged schematic of the puddle region (not to scale).

to the microstructural feature size (μm). Control of the geometry on a large scale may involve putting patterns on the product (e.g. consider a logo being templated onto a branded product) or putting well-defined structural features on the product (e.g. holes in the product which would normally be drilled in post-processing). Control of the properties may involve producing mechanical property gradients (e.g. a ribbon with a hard, scratch resistant surface and a softer, ductile core), magnetic or chemical property gradients. Ultimately, whatever the length-scale, such control requires manipulation of the cooling rate on a length scale much smaller than the overall product length.

We are interested primarily here in controlling the properties on a local level, that is to say, controlling the properties at different points on the ribbon. The properties of the cast product are controlled by the microstructure which is determined from the cooling rate, hence we seek to manipulate the cooling rate.

The approach in this work has two components, loosely categorized as the science and technology steps. The scientific step requires estimating the typical cooling rates involved in the process to use as a baseline. An estimate of the gross or macroscopic cooling rate in the process can be made by relating the residence time of a material packet in the puddle to the solidification velocity using a well known macroscopic mass balance [6]. The macroscopic measurements provide an order of magnitude measurement of the cooling rates. More detailed measurement of the cooling rate comes from using standard methods in the metallurgical literature, which relate dendrite size to cooling rates. This latter technique allows the cooling rate to be characterized through the thickness, as well as along a length of ribbon.

We aim to use the technology component to manipulate the cooling rates, measured using the techniques described above, and indirectly influence the microstructure and properties of Al–7 wt%Si ribbon. Two methods of altering the cooling rate are possible. We refer to the first as negative thermal modification. The idea is to condition the wheel surface using an insulating material (e.g. boron nitride) to limit the heat transfer to the wheel. The pattern of insulating material on the wheel surface creates a heat mask and templates a pattern onto the solidifying material. The second method, explored in this work, which we refer to as direct thermal modification, involves heating the wheel or puddle to change the local temperature gradient (<1 mm scale). The concept of thermal modification to condition the wheel surface was explored by Lee and Hong [7], where they either heated the entire wheel or covered it entirely with an insulating material. Our approach is different in that we locally modify the cooling rate. In this paper, we use a laser to locally heat either the wheel or puddle. The heat delivered by the laser slows the cooling of the melt in a small area, equivalent to the diameter of the laser beam, thus allowing us to create localized areas (of the order of 50 μm) of lower cooling rate, dissimilar microstructure and ultimately dissimilar properties. The technology allows patterns to be 'templated' onto the ribbon and microstructure gradients to be established. The concept is termed 'casting-by-design', i.e., a process whereby patterns, cuts, band lines, corrugations, etc., can be formed on the product during the actual solidification event, thus avoiding the need to perform these operations downstream [8]. The net result is a faster, integrated process and concomitant cost and energy savings. This work demonstrates a 'proof-of-concept' for this technology.

## 2. Cooling rates and microstructure

A widely used method of characterizing microstructural refinement is measuring dendritic feature size, such as primary or secondary arm spacing. However, it is well known that identifying secondary dendrite arms, in particular, and measuring their spacing in rapidly quenched materials is difficult and requires some skill and judgement [9]. Dendrite cell size was correlated with cooling rate by Spear and Gardner [10]. Although this correlation was made over a narrow range of cooling rates, it was later shown that it can be extrapolated over at least eight orders of magnitude of cooling rate [11].

Dendrite size depends on solute transport, and two factors can affect this. One is cooling rate: faster cooling prohibits long range diffusion of solute and therefore dendrite sizes are small. The other is macrosegregation (i.e., phase segregation on a length scale larger than the microstructural feature size). To use microstructure as a measure of cooling rate, macrosegregation must first be ruled out. The high cooling rates in melt spinning eliminate macrosegregation [12].

Since the size of dendritic features is a function only of the amount of time they have to form, feature size can be used to measure local cooling rate. The following relationship between secondary dendrite arm spacing (SDAS) and the local solidification time $t_s$ has been established by Flemings [13]

$$\lambda = At_s^n \quad (1)$$