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New Chill-Block Melt Spinning Relations to Predict Ribbon Thickness

David J. Kukulka*
State University of New York at Buffalo, Buffalo, New York 14222
Anant Poopisut†
M. W. Kellogg Company, Houston, Texas 77072
and
Joseph C. Mollendorf‡
State University of New York at Buffalo, Buffalo, New York 14260

Nomenclature

A, B, C_b, K	=	equation constant
l	=	liquid puddle length
Q	=	volumetric flow rate
Q_{jet}	=	volumetric jet flow
t	=	ribbon thickness
U_∞	=	liquid velocity
V	=	substrate velocity
w	=	ribbon width
α	=	ejection angle, measured from vertical axis
δl	=	boundary-layer displacement thickness
ν	=	kinematic viscosity

Introduction

AMORPHOUS metallic alloys, sometimes called glassy alloys, are useful materials that have attractive properties that include good corrosion resistance and high fracture strength. Methods that are utilized in producing amorphous metals include vapor condensation, sputtering, ion implantation, and chill-block melt spinning. Chill-block melt spinning is a relatively simple process whose origin dates back into the 1800s. It is widely used in the mass production of a variety of products (i.e., amorphous superalloy brazing alloys, solders, glassy transformer core alloys, and other ferromagnetic products). Pond[1] patented a process that involved ejecting a jet of liquid metal onto the surface of a rotating drum. In chill-block spinning, the material is melted in a crucible and a stream of melt is ejected by pressure through a small orifice onto the circumferential surface of a rotating drum. A liquid puddle forms at the base of the jet and the ribbon is extracted from its underside. Kavesh[2] analyzed the melt puddle in a chill-block melt spinning process by assuming that the viscosity of the liquid outside the solidified layer is constant and that no thermal resistance exists at the liquid melt/substrate interface. He showed that the thermal boundary-layer thickness was three to nine times thicker than the momentum thickness. Hillmann and Hilzinger[3] studied $Fe_{40}Ni_{40}P_{14}B_6$ and found that at a constant ejection pressure the height of the puddle was of secondary importance and that the dimensions of the ribbon could be determined by the length and width of the puddle. Liebermann[4] developed an experimental relation and found no significant effect of melt superheat on the geometry of ribbons produced from $Fe_{40}Ni_{40}B_{20}$ and $Fe_{83}B_{15}Si_2$. Vincent et al.[5] calculated the rate of the propagation of the solid front by assuming a heat transfer coefficient and found that the solid front velocity was too low to account for the final ribbon thickness. They concluded that the solid ribbon thickness is related primarily to the propagation of the momentum. Vincent et al. presents a discussion supporting momentum control as being dominant in the chill-block melt spinning process.

Pavuna[6] experimentally studied chill-block melt spinning over a wide range of volumetric flow rates for a melt with an approximate dynamic viscosity of 965 mm^2/s. For flow rates up to 4 cm^3/s Liebermann's[4] relation is supported, whereas for higher flow rates (from 4 to 7 cm^3/s) the data agree with the relations of Kavesh.[2] Pavuna[6] concludes that ribbon width is primarily controlled by the normal component of the volumetric flow rate and that the injection angle may influence both ribbon width and thickness.

Anestiev and Russeo[7] proposed a relationship between the puddle length, volumetric flow rate, surface velocity, impingement angle, and nozzle diameter. Anestiev[8] presented a system of equations that uses casting parameters and several physical properties of the melt to predict ribbon thickness. These results show good agreement with experimental data, but require the use of a series of equations to obtain results. In a later study, Anestiev[9] considered the existence of a heat transfer resistance on the puddle-substrate contact area and the latent heat of fusion separation on the liquid–solid interface. Finally, Taha et al.[10] graphically investigated the variation of ribbon geometry as a function of substrate velocity, injection pressure, substrate thermal conductivity, melt superheat, nozzle/substrate height, and nozzle diameter.

Proposed Relations

The present study proposes two empirical relations that predict ribbon thickness for a wide range of volumetric flow rates (where $Q = Vwt$). The first relation is based on experimental data, whereas the second uses a momentum transport control analysis. Since ribbon formation is complex in nature, it is difficult for a simple relation to describe a wide range of conditions. Based on the form of previous works, the general form of the proposed relations can be taken as

$$t \sim Q^A/V^B \tag{1}$$

$$w \sim Q^{1-A}/V^{1-B} \tag{2}$$

Pavuna[6] reported that both Kavesh's[2] and Liebermann's[4] relations could not describe the entire range of his experimental

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*Professor, Department of Mechanical Engineering Technology, 1300 Elmwood Avenue.

†Research Engineer.

‡Professor, Department of Mechanical and Aerospace Engineering.

Table 1 Values of *B* for various materials and flow rates

Q, mm^3/s	Material	B
70–600	$Fe_{40}Ni_{40}B_{16}P_4$	0.83
1000–3000	$Cu_{66}Ti_{34}$	
	$Cu_{60}Zr_{40}$	0.80
	$Cu_{27}Zr_{73}$	
4000–6000	$Cu_{27}Zr_{73}$	0.78

data. Liebermann's relation could only describe the experimental data for low flow rates and Kavesh's were valid only for high flow rates.[2] For flow rates larger than 4500 mm^3/s the difference between predicted and experimental values is in the range of 30–40%. This suggests that the ribbon thickness relation may not be linear and that a complex fluid flow situation may exist. Furthermore, A and B in Eq. (1) may not be constant over the range of flow rates considered. The results of Hillmann and Hilzinger[3] show that for a constant volumetric flow rate and $B \approx 0.8$, A is nearly constant. However, Pavuna[6] shows that B changes significantly as the flow rate or ejection angle varies. At constant velocity, with increasing flow rate or ejection angle, B decreases. To account for ejection angle, a $1 - \cos\alpha$ term is included in the following ribbon thickness relation:

$$t = K\{Q/(1 - \cos\alpha)\}^A/V^{B - Cb\{Q/(1-\cos\alpha)\}} \tag{3}$$

where C_b is approximately 0.008 cm^3/s. This relation is based on experimental data and predicts t over a wide range of volumetric flow rates. It agrees with experimental data[2,4,6] to within ±18%. Values of B are given in Table 1 for different materials and flow rates.

In the chill-block process, liquid metal is ejected from the nozzle and impacts the drum surface, dividing into an upstream and downstream flow. The upstream flow counters the liquid metal and is dragged along by the drum while the downward momentum pulls the liquid jet. Mixing occurs in the region where the liquid puddle is formed, whereas downstream does not have significant mixing and a stable layer is formed. As you reach the end of the liquid puddle the upper surface velocity of the puddle increases from jet velocity to substrate velocity.

Applying the conservation of mass and assuming steady-state conditions, an incompressible fluid, constant properties, and U_∞ being constant yield:

$$\delta l = 1.721[\nu x/(V - U_\infty)]^{0.5} \tag{4}$$

In the process, U_∞ actually varies from less than jet velocity to larger than jet velocity, whereas at the end of the puddle it is equal to drum velocity. If an exact analysis is desired, each section should be analyzed and then integrated over the puddle length. However, this would not yield a general solution since the jet velocity and drum velocity changes with the puddle shape, whereas the velocity profile is changing in each section.

Pavuna[6] reports that $Q \cos\alpha = A_{\text{jet}}V_{\text{jet}} \cos\alpha$. For simplicity assume that $U_\infty \approx V_{\text{jet}} \cos\alpha$, thus Eq. (4) becomes

$$t = 1.721[\nu l/(V - V_{\text{jet}} \cos\alpha)]^{0.5} \tag{5}$$

Vincent et al.[5] suggest considering $U_\infty = 0$, yielding

$$t = 1.721[\nu l/V]^{0.5} \tag{6}$$

Results and Discussion

A comparison of values of t for constant ejection pressure with constant flow rates is given in Table 2 and shows that the proposed relation improves the accuracy of the calculated results. Therefore, the term $(V - V_{\text{jet}} \cos\alpha)$ should be included in the ribbon thickness relation instead of simply V. The momentum transport model gives a reasonable result, but has the disadvantage of requiring puddle length to be measured or known before the thickness can be computed. The general form of the relation is $t = K_m Q^A/(V - V_{\text{jet}} \cos\alpha)^B$, where K_m, A, and B are taken from experimental data. Using experimental data,[2,4,6] the relation becomes

$$t = 1.585Q^{0.17}/(V - V_{\text{jet}} \cos\alpha)^{0.8} \tag{7}$$

When compared to the previously reported data of Kavesh,[2] Liebermann,[4] and Pavuna,[6] this relation predicts the thickness of the ribbon with an accuracy of ±15%.

Table 2 Experimental ribbon thickness data t_{exp} of Hillmann and Hilzinger[3] compared to calculated thickness values

			Calculated thickness			
V, m/s	l, mm	t_{exp}, μm	[a], μm	[b], μm	[c], μm	[d], μm
15	5.3	56	48.0	53.66	58.78	56.5
30	3.6	31	28.3	29.83	31.00	29
60	2.7	16.5	17.0	17.44	17.76	16

[a]Vincent et al.[5]
[b]Equation (5) with $V_{\text{jet}} = 3$ m/s.
[c]Equation (5) with $V_{\text{jet}} = 5$ m/s.
[d]System of equations.[8]

Jet velocity is one of several parameters that controls the puddle geometry. At low jet velocities and high substrate velocities, the liquid jet breaks up into droplets. If the jet velocity is increased, the liquid puddle will only form on the drum surface underneath the nozzle. At high jet velocities and low substrate velocities the puddle length will be extended. Therefore, the relative velocity between jet and substrate velocity decides on the regime and geometry of the puddle.

Equation (7) accounts for different jet velocities and it can be shown that at the same flow rate, for higher jet velocities, a slightly thicker ribbon will be produced than at lower velocities. The experimental results of Liebermann[4] and Pavuna[6] confirm that increasing the jet velocity (smaller nozzle diameter) extends the puddle length and results in a thicker ribbon. Consider $(V - V_{\text{jet}})^B$, where B is constant. If V is constant, then let $(V - V_{\text{jet}})^B$ be equal to V^C. Any reduction in V_{jet} will cause an increase to $V - V_{\text{jet}}$, which results in an increase to C, and when V_{jet} is increased, C will decrease. By increasing V_{jet}, the puddle length will increase and at the same time the relative velocity $V - V_{\text{jet}}$ will decrease, resulting in an increase in displacement thickness. Regardless if momentum or thermal transport is in control, increasing the puddle length and reducing the relative velocity will cause an increase in the residence time underneath the puddle, thereby, resulting in a ribbon thickness increase.

In using either the momentum transport control or thermal transport control model, the general empirical relational form can be written as $t = KQ^A/V^B$, with A being a weak function of volumetric flow rate and substrate velocity, whereas B varies with volumetric flow rate. This study suggests that thickness prediction can be improved by including a $(V - V_{\text{jet}} \cos\alpha)$ term.

Two simple new relations are proposed that predict ribbon thickness for a wide range of flow rates and they are given as

$$t = K\{Q/(1 - \cos\alpha)\}^A/V^{B - Cb\{Q/(1-\cos\alpha)\}} \tag{8}$$

$$t = KQ^A/(V - V_{\text{jet}} \cos\alpha)^B \tag{9}$$

where K, A, B, and C_b are constants obtained from experimental data. They predict ribbon thickness for a wide range of volumetric flow rates with an accuracy of ±18% when compared to previously reported data.[2,4,6]

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Emittance Measurements for a Thin Liquid Sheet Flow

Amy N. Englehart*
Cleveland State University, Cleveland, Ohio 44115
Marc W. McConley†
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
and
Donald L. Chubb‡
NASA Lewis Research Center, Cleveland, Ohio 44135

Introduction

THE liquid sheet radiator (LSR) is an external flow radiator that uses a triangular-shaped flowing liquid sheet as the radiating surface. It has potentially much lower mass than solid wall radiators such as pumped loop and heat pipe radiators, along with being nearly immune to micrometeoroid penetration. The LSR has an added advantage of simplicity. Surface tension causes a thin (100–300-μm) liquid sheet to coalesce to a point, causing the sheet flow to have a triangular shape. Such a triangular sheet is desirable since it allows for simple collection of the flow at a single point.

A major problem for all external flow radiators is the requirement that the working fluid be of very low (~10^{-8} torr) vapor pressure to keep evaporative losses low. As a result, working fluids are limited to certain oils (such as used in diffusion pumps) for low temperatures (300–400 K) and liquid metals for higher temperatures.

Previous research on the LSR has been directed at understanding the fluid mechanics of thin sheet flows[1,2] and assessing the stability of such flows, especially with regard to the formation of holes in the sheet.[3] Taylor[4–6] studied extensively the stability of thin liquid sheets both theoretically and experimentally. He showed that thin sheets in a vacuum are stable. The latest research has been directed at determining the emittance of thin sheet flows. The emittance was calculated from spectral transmittance data for the Dow Corning 705 silicone oil. By experimentally setting up a sheet flow, the emittance was also determined as a function of measurable quantities, most importantly, the temperature drop between the top of the sheet and the temperature at the coalescence point of the sheet. Temperature fluctuations upstream of the liquid sheet were a potential problem in the analysis and were investigated.

Analysis and Results

Sheet Emittance from Transmittance Data

The following expression is given for the spectral emittance ε_λ of an infinite sheet,[1]

$$\varepsilon_\lambda = 1 - t_\lambda = 1 - 2E_3(\alpha_\lambda \tau) \tag{1}$$

where t_λ is the spectral transmittance, α_λ is the extinction coefficient, τ is the thickness of the sheet, and $E_3(x)$ is the exponential integral of order three. In obtaining Eq. (1) reflection at the vacuum, sheet interface has been neglected. Including all reflection results in a more complex expression for the emittance.[7] The major correction to Eq. (1) is that it should be multiplied by $(1 - R)$, where R is the reflectance at the vacuum-sheet interface. Using an index of refraction, $n = 1.58$,[8] results in a normal reflectance of $R = (n - 1)^2/(n + 1)^2 = 0.05$. Therefore, to first order, the inclusion of reflectance results in a less than 10% correction to Eq. (1). The total hemispherical emittance is defined as follows[9]:

$$\varepsilon = \frac{\int_0^\infty \varepsilon_\lambda e_{\lambda_b}(\lambda, T)\, d\lambda}{\sigma_{sb} T^4} \tag{2}$$

where $e_{\lambda b}$ is the blackbody hemispherical spectral emissive power, T is the temperature, λ is the wavelength, and σ_{sb} is the Stefan–Boltzmann constant (5.67×10^{-8} W/m^2 K^4).

From the measured spectral transmission of the oil t_λ, the extinction coefficient α_λ is calculated as given in Ref. 10. The total emittance ε is then calculated for any thickness τ, and any temperature T, using Eqs. (1) and (2). Transmittance data were taken for a sample of the Dow Corning 705 silicone oil with a Fourier transform infrared (FTIR) spectrophotometer. From this transmittance data, the extinction coefficient was determined,[10] and the extinction coefficient is plotted as a function of wavelength in Fig. 1. A further advantage of Dow Corning 705 silicone oil is the extinction coefficient's maximum around 9–10 μm. For 300–400 K, the blackbody hemispherical emissive power is a maximum at 8–10 μm. Because

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*Student, Department of Electrical Engineering, 1983 E. 24th Street.

†Ph.D. Candidate, Aeronautics and Astronautics, Draper Laboratory, M/S 3-H, 555 Technology Square. Student Member AIAA.

‡Research Engineer, Photovoltaics Branch, 21000 Brookpark Road. Member AIAA.