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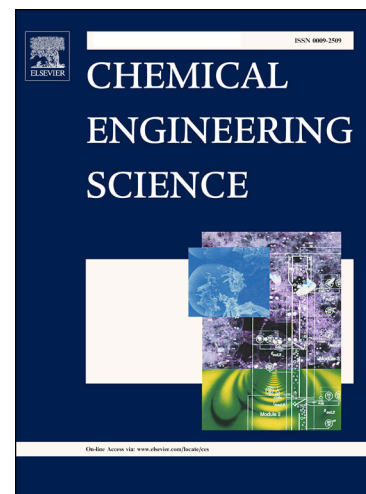
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# Rapid solidification forming of glassy and crystalline ribbons by planar flow casting

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## Abstract

Emerging products for an ultra-energy-efficient economy demand new amorphous and nanocrystalline thin metallic glass (TMG) alloys. Planar flow casting (PFC) is the rapid solidification process of choice for forming TMGs. In this paper, TMG and crystalline alloys are demonstrated to process similarly by PFC despite their well-known different solid-state atomic structures. The high-fragility of the TMG alloy is argued to be responsible. A simple scaling law for ribbon thickness is reported. Thickness depends on the thermal properties of the alloy and heat transfer characteristic of the PFC machine. Perhaps surprisingly, explicit knowledge of the viscosity of the glass is not needed. Dimensional reasoning, mathematical modeling and experiment for two different alloys on two different PFC machines are the methods employed.

**Keywords:** amorphous, casting, crystallization, metallic glass, processing, rapid solidification

## Highlights

- Rapid solidification processing by PFC to thin glassy (TMG) ribbon is the focus
- Contrast to crystalline (XTL) ribbon by thickness and puddle observation is employed
- Heat transfer limit yields thickness scaling law that collapses both TMG and XTL data
- Five dimensionless groups correlate thickness to processing and material parameters
- By macroscale metrics, fragile TMGs process similarly to XTL alloys, surprisingly

## 1. Introduction

A metallic glass forms on solidification when the motion of the constituent atoms of the alloy are sufficiently frustrated. This frustration can happen owing to a mismatch in atomic sizes or by a sufficiently high cooling rate. Without this frustration, as in conventional solidification where cooling rates are typically much slower, alloys solidify to a crystalline atomic structure. Mismatch accommodates slower cooling and favors a thicker product like bulk metallic glasses (BMGs). On the other hand, rapid cooling accommodates lesser disparity in atomic size but requires larger surface-to-volume ratios, favoring thin metallic glasses (TMGs). Planar flow casting (PFC) is the process used to fabricate TMGs.

New TMG alloys will enable advanced high-performance products for manipulation of electromagnetic forces and fields. One of the major applications for TMGs are as power distribution transformers cores. Hasegawa cites in 2008 that TMG transformer cores have the potential to reduce annual CO<sub>2</sub> production by 60M tonne in the USA alone[18]. These materials are crucial to an ultra-energy-efficient economy. Because amorphous metals provide high magnetic saturation at low magnetic losses, they enable favorable electromagnetics in applications of actuation, sensing or shielding, among others. For example, amorphous alloys are envisioned for superior torque motors in new electric vehicles [12, 28].

The favorable electromagnetic, mechanical and chemical macro-scale properties of glassy materials are due to their liquid-like atomic scale structures. That liquid metals could be quenched sufficiently rapidly to achieve a glassy state was first demonstrated using the splat-quench technique[23]. Continuous fabrication into thin glassy ribbons became possible with the invention of the planar-flow casting technique[25]. Today PFC is used to manufacture ultra-efficient transformer core materials [18], telecom and automotive devices[16], electronic article surveillance tags [17], and corrosion resistant braze foils[24, 27, 26], among others. Nevertheless, PFC remains poorly understood because of its complexity at fast and small scales. PFC produces ribbon at speeds of up to thirty meters per second (sixty-seven mph) solidified within a millimeter-sized zone where flowing molten metal contacts a cooling surface to freeze at rates of up to a million degrees per second.

Rapid solidification processing by PFC to TMG ribbons is the focus of this paper. We demonstrate that on the processing scale the PFC of metallic glasses behaves similarly to the casting of crystalline alloys. We quench two different alloys, Table 1. The first, an Al-7Si alloy with liquidus temperature at 614°C, solidifies to a polycrystalline structure. Planar flow processing of this alloy is well studied[2, 8, 33]. In contrast, the second alloy, a NiCrP alloy (Metglas brazing foil, MBF) is a glass former with liquidus temperature at 934°C. It is rapidly solidified to a glassy structure, referred to as vitrification. The processing of TMGs like MBF is less well documented than that of crystalline or bulk metallic glass alloys. By identifying appropriate lengths and time scales, dimensional reasoning leads to a functional form that unifies the processing data of both crystalline

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