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Rheological Behaviour of Semisolid A356 Alloy Slurry during Cooling – An Overview

Sudip Simlandi
Department of Mechanical Engineering, Jadavpur University, Kolkata, West Bengal, India

ABSTRACT

In present days, the semisolid metal forming (SSF) is an emerging casting technique for producing critical automotive, military and aerospace components. The essence of the SSF process relies primarily on distinct rheological behaviour of the alloy during casting under shear. The rheology of slurries has to be properly understood for successful implication of the SSF process. In this work, the author presented an overview of the rheological behavior of semisolid A356 alloy under cooling. The author discussed on model for evolution of structural parameter and apparent viscosity of the semisolid slurry under cooling.

Keywords : Solidification, Stirring, Semisolid slurry, Rheology and Apparent viscosity

I. INTRODUCTION

In different applications of casting, dendritic microstructure is not desirable as it results in poor mechanical properties. One of the ways to suppress this dendritic growth is to augment the fluid flow in the mushy zone by stirring (Spencer *et al.* [1], Vives [2], Joly and Mehrabian [3], Flemings [4]). The enhanced fluid flow detaches the dendrites from the solid-liquid interface and carries them into the melt to form slurry. When this slurry solidifies, the microstructure is characterized by globular, non-dendritic primary phase particles, separated and enclosed by a near-eutectic lower-melting second phase. The globular microstructures in the semisolid range offers less resistance to flow even at high solid fraction. The above principle is the basis of a new manufacturing technology called the "Semi-solid forming" (SSF). This SSF process offers significant benefits in product quality and productivity, primarily because of the non-turbulent filling of the die, which results from controllable viscosity of the semi-solid slurry. Since flow stress, shrinkage porosity and thermal stress are also lower, the SSF process has the capability of forming intricate and near-net-shaped parts. Recently, the SSF process is a developing technique in India and much effort has been given to commercialize the technique. There are two basic forming methods of the SSF process, namely Rheocasting and Thixocasting (Flemings [4]). In a typical rheocasting process, the semi-solid slurry is prepared in presence of stirring directly beside a die and the slurry is immediately cast into parts in the die. On the other hand, in the thixocasting process, the billets having non-dendritic microstructure are first produced through a direct chilled (DC) casting operation along with stirring. These non-dendritic billets are called 'raw materials' for further processing. Subsequently, this raw material is reheated to a temperature in the "mushy" zone and processed into final parts using a die-casting machine. The continuous casting in presence of stirring involves cooling, solidification of the melt, fragmentation of dendrites at the solid-liquid interface and the transport of fragmented dendrites in the bulk liquid, and finally the formation of semi-solid slurry which have distinct rheology. The transport phenomenon during the solidification process in presence of stirring is fairly complex because of the movement of fragmented dendrites and the distinct rheological behaviour of the slurry. The rheological behaviour of the slurry and the transport phenomena during solidification are not well known. It is also found that the numerical models related to the SSF process are less developed and the experimental prediction is more expensive. It is also observed that, the viscosity of the slurry during processing depends mainly on the microstructures and the solid-fraction presents in the slurry. Therefore, in this review, the author present literature on evolution of microstructure and solid fraction during solidification under shear and subsequently on the modeling of rheology.

II. MODELLING OF RHEOLOGY OF SEMISOLID SLURRY DURING CONTINUOUS COOLING

It is already stated that, in rheocasting, the alloy is sheared continuously during solidification and a semisolid slurry forms which exhibits a complex non-Newtonian flow behavior. Therefore, a review on rheological behaviour is necessary for understanding of the above process. The modelling based rheological behaviour is reviewed during continuous cooling. In this context, the related research works are reviewed for understanding of the rheological behaviour of alloy during cooling. Fleming *et al.* [4] studied experimentally the rheological behavior of a semi-solid alloy (Al-4.5 % Cu) during continuous cooling. They found that the apparent viscosity shows a gradual variation at low fraction of solid of about 0.5 and then increases sharply with a small increase in fraction of solid. Barman *et al.* [5, 6] presented the rheological behavior of a semisolid aluminium alloy (A356) experimentally using a concentric cylinder viscometer. Atkinson [7] and Fan [8] reviewed the effect of process parameters such as shear rate, cooling rate and microstructures on the rheology of the semisolid slurries, and they presented few models for the slurry rheology. Burgos *et al.* [9] presented the kinetics of the agglomeration and de-agglomeration of the suspended particles in the slurry using a structural parameter which depends mainly on shear rate and shear stress. Alexandrou *et al.* [10, 11] presented the non-Newtonian behaviour of the slurry using the Herschel–Bulkley model where the shear stress is represented by multiplying the yield strength of the slurry with the structural parameter. Keung *et al.* [12] found that the yield strength of the slurry depends on the temperature of the slurry and they experimentally determined the yield stress of A356 alloy in the semisolid state. Simlandi *et al.* [13] developed a model to predict the rheological behavior of an Al-alloy (A356) in semisolid state where the alloy is sheared between two parallel plates during continuous cooling. They considered a flow (2-D) of a semisolid alloy (A356) between two parallel plates. The corresponding flow field is represented by the momentum conservation equation. They represented the non-Newtonian behavior of the semisolid slurry considering the shear stress based on the Herschel–Bulkley model as

$$\tau = \left[\frac{\tau_0(\lambda)}{\dot{\gamma}} + K\dot{\gamma}^{n-1}\right]\dot{\gamma} \qquad (1)$$

where the rate of strain ($\dot{\gamma}$) is given as $\dot{\gamma} = \frac{\partial u}{\partial y}$ and $\tau_0(\lambda) = \lambda\tau_0$. The structural parameter (λ) represents the time dependent semisolid behavior, which is first introduced by Burgos *et al.* [15]. The structural parameter (λ) characterizes the state of the structure of the solid particles in the semisolid alloys. In a fully structured state, i.e., when all the particles are connected, λ is assumed to be unity. In a fully broken state, when none of the particles are connected, λ is assumed to be zero. The evolution of this structural parameter is defined by a first-order rate equation. It is assumed that the rate of break-down (de-agglomeration) depends on the fraction of links existing at any instant and on the deformation rate. Similarly, the rate of build-up (agglomeration) is assumed to be proportional to the fraction of links remained to be formed. When shear rate increases, the break-down occurs and vice-versa. In their work (Burgos *et al.* [15]), the evolution of the structural parameter (λ) with time (*t*) is considered as

$$\frac{D\lambda}{Dt} = \alpha_0(1-\lambda) - \alpha_1\lambda\dot{\gamma}\exp(\alpha_2\dot{\gamma}) \qquad (2)$$

The yield stress (τ_o) of the slurry depends on the temperature of the slurry (Keung *et al.* [12]). The temperature field in the domain is predicted considering the energy equation (Simlandi *et al.* [13]) as

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial y^2} \qquad (3)$$

where the yield stress (τ_o) for A356 alloy is calculated as

$$\tau_0 = 4.0 \times 10^{49} \times \exp(-0.181 \times T) \qquad (4)$$

Simlandi *et al.* [13] predicted an apparent viscosity (μ_a) based on the eqns. (1-4). The evolution of structural parameter at different shear rates in Figure 1 and variation of apparent viscosity with fraction of solid at different shear and cooling rates are given in Figures 2 and 3 respectively.

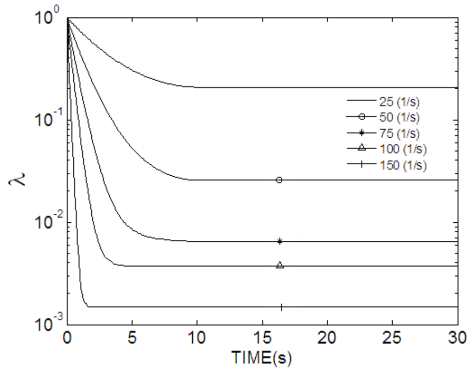

Figure 1. Evolution of λ with time under different shear rates [$\alpha_0 = \alpha_1 = \alpha_2 = 0.01$] (Simlandi et al. [13])

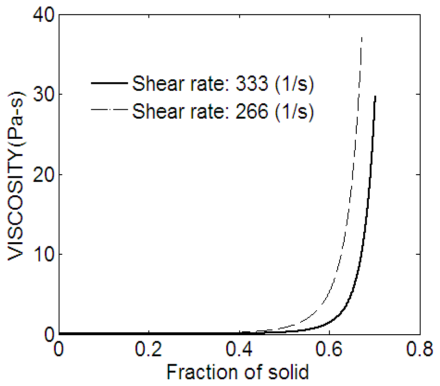

Figure 2. Variation of apparent viscosity with fraction of solid during cooling for different shear rates (at cooling rate of 5°C/min) (Simlandi et al. [13])

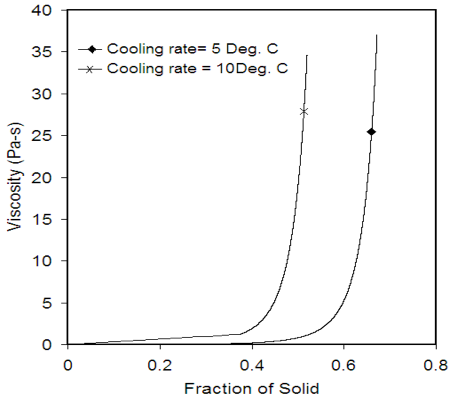

Figure 3. Variation of apparent viscosity with fraction of solid during cooling for different cooling rates (at shear rate of 266 s^{-1}). (Simlandi et al. [13])

III. CONCLUSION

In this work, the author presented an overview of the rheological behavior of alloy in semisolid state during cooling. As the apparent viscosity is a function of shear and cooling rates, the effect of these process parameters on the apparent viscosity is to be studied. It is concluded from the above review that during cooling, apparent viscosity decreases with increasing shear rate and increases with increasing the rate of cooling.

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