Study on the Rheology of AlSi4Mg2 Alloy at Steady State

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Abstract. The rheological characteristics of AlSi4Mg2 alloy at steady state are studied theoretically based on the ICF model. It is shown that the solid volume fraction and shear rate have obvious effect on the rheological behaviour. Specifically, the apparent viscosity increases when the solid volume fraction increases and the shear rate decreases, the corresponding microstructure parameter $n$ has the similar trend. It shows that there is a closely relationship between the steady state viscosity and its microstructure. The AlSi4Mg2 alloy has the pseudoplastic behaviour. The agreement of theoretical prediction and the experimental results indicates the ICF model is reliable to predict the rheological behaviour of AlSi4Mg2.

1. Introduction

Semisolid metal (SSM) forming is catching more and more theoretical and technical attentions because of its distinctive potential in near-net shaping\cite{1}. In recent years, the light alloys have been studied extensively since its excellent characteristics have important effects on SSM processing\cite{2-9}. Among them, as the most abundant metal on earth, aluminium alloys have the low-cost property, which are applied extensively to automobile and aerospace\cite{2-5,8,9}. Thus, the study on the rheological behavior of AlSi4Mg2 alloy has significant meaning for the improvement and the development of SSM processing. Here, the ICF model\cite{8} is used to study the rheological behavior of AlSi4Mg2 alloy at steady state.

2. ICF model at steady state

Here is a brief description of ICF model at steady state. When a SSM slurry is at steady state, its apparent viscosity can be presented as \cite{8}

$$\eta = \frac{\eta_0}{(1-\Phi_{\text{eff}})^{2.5}}$$

where, $\eta$ is the viscosity of the SSM, $\eta_0$ is the viscosity of the liquid, $\Phi_{\text{eff}}$ represents the effective solid volume fraction, which is formulated as\cite{8}

$$\Phi_{\text{eff}} = \left(1 + \frac{B}{\eta_e}\right)\Phi$$

where, $B$ reflects the packing mode of particles, which is given by\cite{8}

$$B = f_1\eta_e^{f_2} + f_3$$

where, $f_1$, $f_2$, $f_3$ are the material constants. Subsequently, the effective solid volume fraction is formulated as
\[ \Phi_{\text{eff}} = \left(1 + \frac{B}{n_e}\right)\Phi = \left(1 + f_{\text{eff}} + f_{\text{eff}}\right)\Phi \]

where, \(n_e\) is the average agglomerate size when the slurry is at steady state, which is

\[ n_e = 1 + \frac{2N_0P_a}{K_d} = 1 + \frac{12\Phi^2K_a}{\pi d^3K_d} \]

Generally, the rheological behavior of SSMS at steady state under a simple shear flow can be described by the above equations completely. The parameters of the ICF model can be found in Ref.[8].

3. Results and Discussion

The apparent viscosity is an important parameter to reveal the rheological behavior of SSM slurry and its dynamics in the process of SSM formation. Therefore, the factors affecting the apparent viscosity of AlSi4Mg2 alloy has been analysed in detail in this paper.

3.1. Effects of solid volume fraction

Fig.1 shows the calculated steady state viscosity and the corresponding average agglomerate size varying with the solid volume fraction. Fig.1(a) compares the present theoretical prediction with the experimental results measured by Zhou et al.[9]. As shown in Fig.1(a), the calculated steady state viscosity are in agreement with the experimental data under different shear rate. Fig.1(a) also shows that the steady state viscosity increases when solid volume fraction increases, which are in agreement with the experimental results[10]. Additionally, it can be seen from Fig.1(b) that the corresponding average agglomerate size varies with the solid volume fraction in the same trend as Fig.1(a). It indicates that there is a close correlation between the apparent viscosity and its average agglomerate size.

![Figure 1. Variation of the calculated steady state viscosity and the average agglomerate size with the solid volume fraction under different shear rates for the AlSi4Mg2 alloy.](image)
3.2. Effects of shear rate

As we know, the shear rate affects significantly the viscosity of the SSM at steady state. Fig. 3(a) shows that the calculated viscosity of AlSi4Mg2 alloy decreases gradually when the shear rate varies from 100s\(^{-1}\) to 550s\(^{-1}\), that is, the present aluminum alloy appears the property of “shear-thinning”, which agrees qualitatively with the experimental results [10]. It may be explained as follows. In fact, according to equation (1) - equation (4), it is found easily that the steady state viscosity is directly related to the effective solid volume fraction and the effective solid volume fraction is a function of the microstructure. This can be identified by Fig.3(b). As shown in Fig.3(b), the average agglomerate size decreases when the shear rate increases under different solid volume fractions varying from 0.25 to 0.35. In both Fig.3(a) and Fig.3(b), the trends of the lines are similar. The coupling between the apparent viscosity and its corresponding microstructure are obvious in Fig.3.

![Graph showing variations in viscosity and agglomerate size with shear rate](image)

**Figure 3.** Variation of the calculated steady state viscosity and the average agglomerate size with shear rate under different solid volume fractions for AlSi4Mg2 alloy.
Fig. 4 gives the shear stress changing with the shear rate when the solid volume fraction is 0.25, 0.30, and 0.35, respectively. It shows that the shear stress increases with increasing the shear rate and the solid volume fraction, respectively, which is consistent with the experimental findings[10].

4. Conclusions
The rheological properties of AlSi4Mg2 alloy at steady state has been investigated theoretically with the ICF model. The effects of solid volume fraction and shear rate on the apparent viscosity and shear stress are shown in this work. Specifically, the apparent viscosity and the average agglomerate increase with increasing the solid volume fraction. This close coupling can be explained by the bridge of effective solid volume fraction. This reflects that the microstructure of the AlSi4Mg2 alloy determines solely its rheological behaviour. Subsequently, the viscosity of the AlSi4Mg2 alloy and its average agglomerate size decreases when the shear rate increase for different solid volume fractions, which means that AlSi4Mg2 alloy has the property of “shear-thinning”. On the whole, the ICF model can offer reliable prediction for the AlSi4Mg2 alloy at steady state.

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