Study on the Time-dependent Rheological Properties of AlSi4Mg2 Alloy

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Abstract. The time-dependent behaviour of AlSi4Mg2 alloy has been investigated with the ICF model. It shows that the apparent viscosity increases with decreasing the shearing time and increasing the resting time, especially at the initial stage. The above variations depend on its microstructure affected by solid volume fraction and shear rate, respectively. It is found that the agglomerating time is about 100 times as long as the deagglomerating time, which agrees with the experiment data.

1. Introduction

It has been about 50 years since Spencer and Flemings [1] firstly invented the Semisolid metal (SSM) processing technique. Nowadays, the SSM forming has been investigated and applied in many aspects[2-4]. The rheological behaviour of SSM has to be studied extensively in order to improve and control the quality of products. Generally, there are two kinds of rheological behavior, that is, steady state behavior and transient state behaviour. Although the behavior at steady state is important for us to study the rheology of SSM, the behaviour at transient state is more useful in the practical SSM forming. Recently, the AlSi alloys have been studied extensively due to its low coefficient of thermal expansion, good wear resistance and heat resistance[5-10]. In this work, the time-dependent rheological behavior of AlSi4Mg2 alloy will be studied on the ICF model.

2. ICF model at transient state

Let us summarize simply the ICF model at transient state. When a SSM is at transient state, its apparent viscosity is [10]

\[ \eta(t) = \frac{\eta_0}{(1 - \Phi_{\text{eff}}(t))^{2.5}}. \] (1)

where, \( \eta(t) \) is the viscosity of the SSM, \( \eta_0 \) is the viscosity of the liquid, and \( \Phi_{\text{eff}}(t) \) represents the effective solid volume fraction at time \( t \), is expressed as [10]

\[ \Phi_{\text{eff}}(t) = \left(1 + \frac{B}{n(t)}\right)\Phi = \left(1 + \frac{f_1 n(t)^{f_2} + f_3}{n(t)}\right)\Phi. \] (2)

where, \( \Phi \) is the solid volume fraction, \( f_1, f_2, f_3 \) are the material parameters, \( B \) is a packing
parameter, \( n(t) \) is the average agglomerate size at any time \( t \). Specifically, which is given by

\[
\frac{1}{n(t)} = \frac{1}{n_e} + \left( \frac{1}{n_0} - \frac{1}{n_e} \right) e^{-\lambda t}.
\]

where, \( \lambda \) is a material parameter, \( n(t), n_0, n_e \) are the average agglomerate size at \( t = t, t = 0 \) and \( t \to \infty \), respectively. The parameter \( n_e \) is formulated as

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

The rheological behavior of SSM at transient state can be described by the combination of equation (1) - equation (4), which are the key equations of ICF model at transient state. The parameters of the ICF model is referred to our first paper[10].

3. Results and Discussion

3.1. Isothermal shearing

We will analyze the effects of isothermal shearing time on the rheological behavior. Here, the time evolution of the microstructure is described in equation (3), where \( n_0 = n(\gamma = 0), n_e = n(\gamma = 400 s^{-1}) \).

Fig.1(a) shows the variation of apparent viscosity with the shearing time and the solid volume fraction. Specifically, as shown in Fig.1(a), the solid volume fraction has an important effect on the apparent viscosity, that is, the apparent viscosity becomes larger when the solid volume fraction is bigger for a given shearing time. It also shows that the apparent viscosity decreases drastically at the initial shearing stage and approaches to a fixed value after about 0.05s. This indicates that the deagglomeration of particles can finish rapidly within about 0.05 seconds. The similar conclusion can be obtained from the average agglomerate size shown in Fig.1(b), which means the close correlation between the apparent viscosity and its microstructure.

![Figure 1. Variation of the calculated apparent viscosity (a) and average agglomerate size (b) with shearing time under different solid volume fractions for AlSi4Mg2 alloy.](image)

When the AlSi4Mg2 alloy is in isothermal shearing process, the effects of shear rate are shown in Fig.2. Specifically, increasing the shear rate(from 400s\(^{-1}\) to 1000s\(^{-1}\) to 2000s\(^{-1}\)), the values of the apparent viscosity and the average agglomerate size decrease for a chosen shearing time. This indicates that the semisolid AlSi4Mg2 alloy is a “shear-thinning” fluid at transient state, which is the same conclusion as the rheological behavior at steady state[10]. Fig. 2 also shows that the deagglomeration time is similar to that as shown in Fig.1.
3.2. Isothermal resting

The AlSi4Mg2 alloy is at its initial state when the shear rate is equal to 500 s$^{-1}$. The agglomeration of particles can be studied when the SSM slurry reaches a new steady state during the isothermal resting (the value of shear rate is zero). During this process, the apparent viscosity increases quickly at the initial stages of resting and then approach nearly a fixed value after a long resting time as shown in Fig. 3(a). Fig.3(b) plots the variation of the average agglomerate size with shearing time. It shows the similar change as in Fig.3(a). Both figures show that the time required to reach the new steady state increases with increasing the solid volume fraction (they are 0.25, 0.30 and 0.35, respectively). Fig. 3 also shows the agglomeration time of particles is about 5 seconds for the present alloy.

The effect of initial shear rate (the values are 100s$^{-1}$, 500s$^{-1}$ and 2000s$^{-1}$, respectively) on isothermal resting for AlSi4Mg2 alloy has been given in Fig.4. It has been noted that the effect of initial shear rate is obvious at the initial resting stage and then disappears gradually after about 5 seconds.

Combining Fig.1-Fig.4, it can be concluded that the deagglomeration is about two orders of magnitude quicker than the agglomeration, which is in qualitative agreement with the experimental findings[1]. This discloses that the rheological route may be better than the thixotropic route[2].
4. Conclusions
The time-dependent rheological behaviour of semisolid AlSi4Mg2 alloy has been studied during isothermal shearing and isothermal resting. It has been shown that the viscosity together with its average agglomeration size depend strongly on the isothermal shearing time and the isothermal resting time. Specifically, the viscosity determined definitely by its microstructure, decreases when the shearing time increases, conversely, and increases when the resting time increases. Additionally, it shows that the break-down of the particles are about 100 times as fast as the build-up of them. This agrees with experiment measurement. Finally, the AlSi4Mg2 alloy own the property of “shear-thinning” when it is at transient state. The present study shows the reliability of ICF model in describing the time-dependent rheological behaviour.

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