The influences of the microstructure morphology of A356 alloy on its rheological behavior in the semi-solid state

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Abstract

In this paper, the rheological behavior of semi-solid A356 alloy with different solid morphology was studied with an improved static shear test method. The results indicated that the rheological behavior of the alloy was significantly influenced by the structural morphology of the alloy. The alloy had quite different rheological properties even though the same fraction of solid existed in the semi-solid state. The rheological behavior of the alloy fitted a five-element model ($H_1$–$[N_1H_2]$–$[N_2S]$) for the as-cast microstructure with developed primary (α-Al dendrites), whereas it fitted a six-element model ($[H_1][S_1]$–$[N_1][H_2]$–$[N_2][S]$) for degenerated dendritic or spheroidal primary α-Al, which had been obtained by electromagnetic stirring and spray deposition, respectively. Computation results showed that the deforming capability and shear rate of the semi-solid alloy increased remarkably with the change of primary α-Al from developed dendrites to degenerated dendrites, and then to spheroidal structures. On the other hand, the temperature dependence of the rheological properties of the semi-solid alloy with spheroidal or degenerated dendritic primary α-Al was much less than that with developed primary α-Al dendrites. © 2001 Published by Elsevier Science Ltd.

Keywords: A356 alloy; Semi-solid state; Solid morphology; Rheological behavior

1. Introduction

Investigation of the rheological behavior of alloys in the semi-solid state is helpful to deeply understand the solidification and mechanical behavior of an alloy. The start of effective shear experiments on Al–Si and Al–Cu alloys can be traced back to the works of Flemings and his co-workers [1,2] in the early 1970s. This led to a realization of the significance of the rheological behavior of alloys in the semi-solid state. A five-element model and its constitutive equation were first put forward to describe the rheological behavior of Al–Si alloy by researchers from the former Soviet Union [3], and the elastic, viscoelastic, and elastic plastic mechanical characteristics of the alloy were revealed using an immersion static shear method [3]. Liu [4] and Chen et al. [5,6] also confirmed that the rheological behavior of Al–Si and Al–Cu alloys corresponded with the five-element model. Since 1990, Chen [7] and Zhang [8] have investigated the rheological properties of 624 steel and Al–Si alloy in the semi-solid state, and pointed out that, in addition to the five-element model, there existed a six-element model indicating the rheological behavior of the experimental alloys within a certain temperature range.

This was also found in other alloy systems, such as ZA27 alloy [9]. Up to now, controversy exists throughout the field, and it is difficult to take a general view of the rheological properties of alloys. Comprehensive and systematical exploratory work is needed to understand the characteristics of alloys in the semi-solid state.

Up to now, a traditional static shear experiment has been mainly used to investigate the rheological properties of alloys in the semi-solid state. This experiment was carried out by loading a constant stress on the sample for a certain period of time and then unloading. The experiment was carried out at different temperatures between the solidus and liquidus. The rheological characteristics of the alloy were deduced from the strain–time curves during loading and unloading. For certain applied stresses, the solid fraction was considered as the only factor that affected the rheological behavior of the alloys. As is well known, the microstructure of alloys is closely related to the solidification conditions. Therefore, solid structure morphology in the alloys in the semi-solid states will inevitably tend to influence their rheological behavior. In this paper, a new experimental method is proposed by means of which the influences of both the solid fraction and structure morphology of alloys could be investigated simultaneously. The improved static shear method is applied to study the
rheological behavior of A356 alloy with developed, degenerated dendritic and spheroidal primary α-Al.

2. Experimental conditions

Specimens with different structure comprised of developed, degenerated dendritic and spheroidal primary α-Al were prepared by traditional casting, using electromagnetic stirring during the solidification process, followed by the spray deposition process. The microstructures of the specimens are shown in Fig. 1.

The improved static shear test was characterized by the specimen design and the way that the pulling rod was loaded (see Fig. 2). The experiments were carried out under a constant stress at certain temperatures between the solidus and liquidus of the alloy. The strain–time curves during loading and unloading processes were recorded. Rheological models were established by analyzing the strain–time curves to describe the rheological behavior of the alloy.

3. Experimental results and analyses

Fig. 3 shows some results of the rheological experiments. It was seen that the rheological curves of the specimens with developed primary α-Al dendrites (see Fig. 3(a) and (c)) had common characteristics as follows:

(i) there existed same instantaneous shear strains at both loading and unloading, and the strain was proportional to the loading stress;
(ii) the shear strain increased gradually with time prolongation after loading, and then the strain decreased step by step with the elapse of time;
(iii) when the loading stress was less than a certain value, there was no residual shear strain, the residual strain only occurring if the load was larger than the critical value.

The rheological characteristics of the specimens with degenerated dendritic and spheroidal primary α-Al can be deduced from Fig. 3(b) and (d) as follows:

(i) it is the loading stress that determines if instantaneous shear strain and instantaneous restitution are engendered at the time of loading and unloading, respectively;
(ii) the phenomena of shear strain increment and decrement emerged at the time of loading and unloading, respectively;
(iii) under certain load, there existed an unrecoverable residual shear strain after unloading. The analyses

Fig. 1. Microstructure of A356 alloy: (a) developed dendrites; (b) degenerated dendrites; (c) spheroids.

Fig. 2. Schematics of the static shear test: (a) traditional method; (b) improved method.
above indicated that the rheological behavior of the alloy coincided with a five-element model \((H_1-[N_1][H_2]-[N_2][S])\) for the structure with developed primary \(\alpha\)-Al dendrites, and a six-element model \([H_1][S_1]-[N_1][H_2]-[N_2][S]\) for that with degenerated dendritic or spheroidal primary \(\alpha\)-Al.

For the five-element model, the constitutive equations were as follows:

\[
\dot{\gamma} = \begin{cases} 
\frac{\dot{\tau} + G_1 + G_2}{G_1 \eta_1} \tau - \frac{G_2}{\eta_1} \gamma, & \text{if } \tau \geq \tau_s, \\
\frac{\dot{\tau}}{G_2} \left( \frac{\dot{\gamma}}{G_1} + \frac{G_1 + G_2}{\eta_2} \right) \tau - \frac{G_2}{\eta_2} \tau - \frac{\eta_1}{G_1} \dot{\gamma} - \gamma, & \text{if } \tau < \tau_s.
\end{cases}
\]

For the six-element model, the constitutive equations were as follows \([8,9]\):

when \(\tau_s > \tau_{s1}\)

\[
\dot{\gamma} = \begin{cases} 
\frac{\tau - G_2 \gamma}{\eta_1}, & \text{if } \tau \leq \tau_{s1} < \tau_s, \\
\frac{\eta_1}{G_2} \left( \frac{\dot{\gamma}}{G_1} + \frac{G_1 + G_2}{\eta_1} \right) \tau - \dot{\gamma}, & \text{if } \tau_{s1} < \tau \leq \tau_s, \\
\frac{\eta_1}{G_2} \left( \frac{\dot{\gamma}}{G_1} + \frac{1}{\eta_2} + \frac{G_2}{G_1 \eta_1} \right) \tau - \dot{\gamma} - \frac{G_2 (\tau - \tau_s)}{\eta_1 \eta_2} \gamma, & \text{if } \tau > \tau_s > \tau_{s1}.
\end{cases}
\]

when \(\tau_s < \tau_{s1}\)

\[
\dot{\gamma} = \begin{cases} 
\frac{\tau - G_2 \gamma}{\eta_1}, & \text{if } \tau \leq \tau_s < \tau_{s1}, \\
\frac{\eta_1}{G_2} \left( \frac{\eta_1 + \eta_2}{\eta_1 \eta_2} \right) \dot{\gamma} + \frac{G_2 (\tau - \tau_s)}{\eta_1 \eta_2} \gamma, & \text{if } \tau_s < \tau \leq \tau_{s1}, \\
\frac{\eta_1}{G_2} \left( \frac{\dot{\gamma}}{G_1} + \frac{1}{\eta_2} + \frac{G_2}{G_1 \eta_1} \right) \tau - \dot{\gamma} - \frac{G_2 (\tau - \tau_s)}{\eta_1 \eta_2} \gamma, & \text{if } \tau > \tau_s > \tau_{s1}.
\end{cases}
\]

Here \(G_1, G_2\) were the shear elastic modulus of the Hooke elastic bodies \((H_1, H_2)\); \(\eta_1, \eta_2\) the viscosity coefficients of Newton viscous bodies \((N_1, N_2)\); \(\tau_s, \tau_{s1}\) were the yield limits of the St. Venant plastic bodies \((S, S_1)\), respectively; and \(\tau, \gamma\) are the loading stresses and shear strains.

4. Discussion

It was found that the five-element model is actually a special case of the six-element model when the yield limit \((\tau_{s1})\) of the St. Venant plastic body \((S_1)\) equals zero. Based on this essential relationship, a general rheological curve could be made out to describe the rheological properties of the alloy under stable shear conditions as shown in Fig. 4. Six parameters were introduced to depict and appraise the rheological characteristics of materials:

(i) instantaneous shearing strain \(\gamma\), which indicated the unrecoverable deformation of semi-solid materials under a certain load after unloading;

(ii) instantaneous restitution shearing strain \(\gamma_2\), which indicated the instantaneous recovering ability of semi-solid materials at the time of unloading;

(iii) stable shearing strain during loading \(\gamma_3\), which indicated the deformation ability of semi-solid materials in general under a certain load;

(iv) residual shearing strain after unloading \(\gamma_4\), which indicated the average shearing strain rate during unloading \(\gamma_5\), where \(t_1\) was the loading time, which indicated the progressing speed towards the stable deformation of semi-solid materials during loading;

(v) average shearing strain rate during unloading \(\gamma_6\), where \(t_2\) was the change to the continuing time after unloading, which indicated the speed of the deformation recovery of semi-solid materials.

An evaluation system of the rheological properties was established on the basis of the six eigenvalues and used to analyze the influences of the microstructure morphology of semi-solid A356 alloy on its rheological behavior. Computation results were shown in Table 1. It was seen that the deformation capability and shearing rate of the semi-solid alloy increased remarkably with the transformation of the
Fig. 3. Results of rheological tests: (a) developed dendrites; (b) degenerated dendrites; (c) developed/degenerated dendrites; (d) spheroids.

Fig. 4. Schematics of the general rheological curve and relative parameters.

primary α-Al from developed dendrites into degenerated dendrites, and then into spheroids. In addition, the dependence of the rheological properties of the alloy with degenerated primary α-Al dendrites on temperature was much less than that for the developed primary α-Al dendrites.

5. Conclusions

1. The microstructure morphology should be considered as one of the important factors influencing the rheological behavior of semi-solid alloys. The effect of both the fraction of solid and the microstructure of semi-solid alloys

| Structure                  | Test condition | $\gamma_1$ ($10^{-5}$) | $\gamma_2$ ($10^{-5}$) | $\gamma_3$ ($10^{-5}$) | $\gamma_4$ ($10^{-5}$) | $\varepsilon_1$ ($10^{-3}$ s$^{-1}$) | $\varepsilon_2$ ($10^{-3}$ s$^{-1}$) |
|----------------------------|----------------|------------------------|------------------------|------------------------|------------------------|--------------------------------------|--------------------------------------|
| Developed primary dendrites| 586°C, 0.78 kPa | 4                      | 4                      | 12.5                   | 0                      | 0.12                                 | 0.03                                 |
|                            | 586°C, 1.17 kPa | 10                     | 10                     | 26                     | 6                      | 0.2                                 | 0.08                                 |
|                            | 594°C, 0.39 Pa  | 10                     | 10                     | 26.5                   | 5                      | 0.24                                 | 0.06                                 |
|                            | 594°C, 0.78 kPa | 16                     | 16                     | 36                     | 3.5                    | 0.27                                 | 0.12                                 |
|                            | 594°C, 1.17 kPa | 24                     | 24                     | 56                     | 13                     | 0.4                                 | 0.21                                 |
| Degenerated primary dendrites| 586°C, 0.39 kPa | 12                     | 0                      | 78                     | 36                     | 1.02                                 | 0.31                                 |
|                            | 586°C, 0.78 kPa | 40                     | 0                      | 126                    | 60                     | 1.23                                 | 0.33                                 |
|                            | 594°C, 0.39 kPa | 30                     | 0                      | 140                    | 90                     | 1.65                                 | 0.38                                 |
|                            | 578°C, 0.52 kPa | 0                      | 0                      | 610                    | 60                     | 1.15                                 | 1.11                                 |
| Spheroids                  | 578°C, 0.78 kPa | 120                    | 120                    | 1360                   | 760                    | 2.39                                 | 1.06                                 |
on the rheological behavior could be successfully investigated by the improved static shear method.

2. At a certain temperature between the solidus and liquidus, i.e. for a certain fraction of solid, the rheological behavior of A356 alloy was strongly affected by its microstructure morphology. The rheological behavior of the semi-solid alloy coincided with the five-element model (H₁−[N₁][H₂]−[N₂][S]) for the microstructure with developed primary α-Al dendrites, and the six-element model ([H₁][S₁]−[N₁][H₂]−[N₂][S]) for the microstructure with degenerated primary α-Al dendrites or primary α-Al spheroids.

3. An evaluation system consisting of six eigenvalues derived from the rheological curves was introduced to describe and appreciate the rheological behavior of semi-solid alloys. Computation results showed that the deforming capability and shearing rate of the semi-solid A356 alloy increased remarkably with the change of the primary α-Al from developed dendrites to degenerated dendrites, and then to spheroids. In addition, the dependence of the rheological properties of the semi-solid alloy with degenerated primary α-Al dendrites on temperature was much less than that for developed primary α-Al dendrites.

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