RHEOLOGICAL PROPERTIES OF SEMI-SOLID Al-Si ALLOY IN SOLID-LIQUID ZONE①

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ABSTRACT The rheological behavior of semi-solid Al-Si alloy in the solid-liquid zone has been investigated with the high-temperature static shear testing rheometer. The rheological parameters of semi-solid Al-Si alloy have been measured. The relationships between the rheological parameters and temperature have been studied. The rheological model and the stress-strain equation of the intrinsic behavior have been illustrated, and the process of evaluating rheological parameters has been mentioned.

Key words semi-solid Al-Si alloy solid-liquid zone rheological property

1 INTRODUCTION

The rheological properties and solidified structure of alloy in the shear flow have been reported by many references since professor Flemings M C[1-3] invented firstly rheocasting and thixocasting in Massachusatts Institute of Technology of U S in the early 1970s. Al-Si alloy is a wide application binary alloy, and Al-Si hypoeutectic alloy has been the object of study in many years. These defects such as hot tearing, segregation, and gas hole, i. e. in the process of alloy solidification are closely related to the rheological properties in the solid-liquid zone. Therefore the rheological behavior of alloy was studied recently using the method of rheology, and the intrinsic models of the stress-strain via temperature in the process of solidification were studied too. In this paper, the rheological behavior of Al-Si alloy in the solid-liquid zone was investigated with the high-temperature static shear testing rheometer, which revealed the intrinsic property of rheology and the form of solid and liquid structure.

2 EXPERIMENTAL

Fig. 1 is a schematic diagram of the measurement apparatus of Al-Si alloy rheological behavior in the solid-liquid zone. The apparatus is made of the heating system, the loading system, casting mold , the temperature controller and the measurement recorder. The heating system and the temperature controller made the recorder

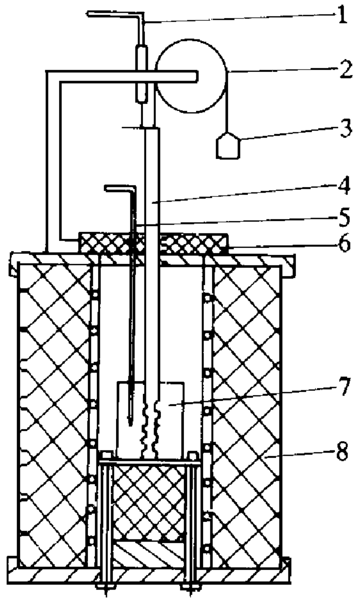

Fig. 1 Schematic diagram of the high-temperature static shear testing apparatus
1 —Displacement transducer; 2 —Pulley; 3 —Load; 4 —Shaft; 5 —Thermocouple; 6 —Insulator; 7 —Casting mold; 8 —Furnace.

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possiblely maintain a scheduled temperature in the solid-liquid zone within 1 ℃ throughout a test. The precisive temperature controller DWK-702 was taken to hold at 1250 ℃ within 0.5 ℃. The displacement transducer AC-LVDT and the function recorder were used to obtain the displacement as the curve of strain-time at the different temperature. The loading and unloading operation were carried out with the loading system.

Al-4.87%Si alloy melt was poured into the casting mold. Adjustment of the precisive temperature controller made it possible maintain a scheduled temperature in the solid-liquid zone. While the obtained temperature of alloy was steady to a demand temperature, the alloy was loaded(0 s) and unloaded(100 s).

The apparatus adopted a pulley system to maintain a constant stress.

$$\tau = P/F \quad (1)$$

where τ is shear stress, P is applied load, F is contact area between alloy and shaft. The shear strain of alloy, γ, is given by

$$\gamma = S/R \quad (2)$$

where S is rising distance of shaft and R is distance between shaft casting mold wall.

It was apparent the alloy system contains Hooke body, which raised to transient deformation γ_H at the point of instantaneous loading (0 s) and unloading (100 s). There was a Kelvin body in the alloy when it raised to elastic aftereffect γ_K after loading and unloading. The permanent deformation γ_B indicated there was Newton body in the alloy. Hence, the deformation which was formed by Bingham body was called viscoplastic strain. When the stress exceeded a certain value the permanent deformation raised. The rheological model of Al-4.87%Si semi-solid alloy is made of series connection among Hooke body, Kelvin body and Bingham body in 600 ℃. The model is shown in Fig. 2, and the structure of model is given by

$$[H_1] - [H_2 | N_2] - [S_B | N_1] \quad (3)$$

where H is Hooke body; N is Newton body and S_B is SaintVenant body; — is series connection; | is parallel connection.

In order to distinguish elastic body, viscoelastic body and viscoplastic body in the rheological model, the visco-elastic-plastic bodies during the process of loading and unloading may be separated. These cases are shown in Fig. 3. the different strain-time function curves can be obtained.

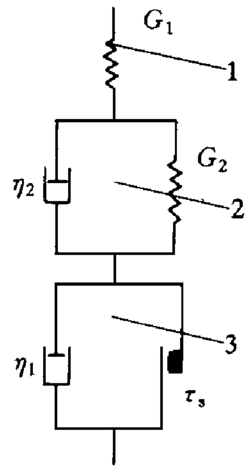

Fig. 2 Rheological model with five elements

1 —Hooke body; 2 —Kelvin body; 3 —Bingham body

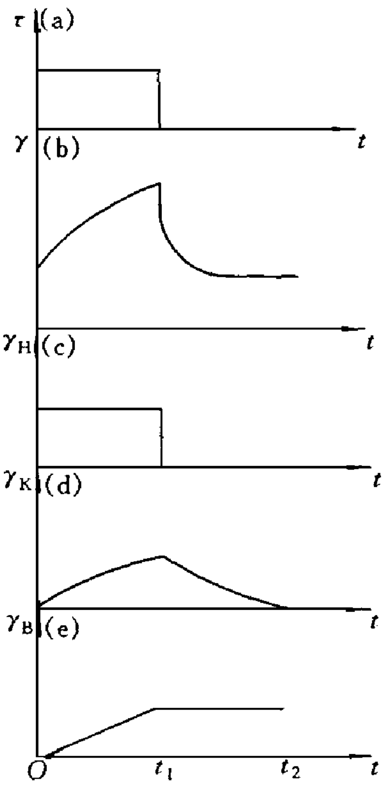

Fig. 3 Separation of visco-elastic-plastic bodies during loading and unloading

3 RESULTS AND DISCUSSION

For an experimental rheological model with five elements, the stress-strain eqs. via Al-Si alloy rheological model in the solid-liquid zone are given by

$$\begin{cases} \dot{\gamma} + G_2\eta_2\gamma = \dfrac{1}{G_2}\dot{\tau} + \dfrac{(G_1+G_2)}{G_2\eta_1}\tau & \tau < \tau_s \\ \ddot{\gamma} + \dfrac{G_2}{\eta_2}\dot{\gamma} = \dfrac{1}{G_1}\ddot{\tau} + \left(\dfrac{1}{\eta_1} + \dfrac{1}{\eta_2} + \dfrac{G_2}{G_1\eta_2}\right)\dot{\tau} + \dfrac{G_2}{\eta_1\eta_2}(\tau - \tau_s) & \tau > \tau_s \end{cases} \quad (4)$$

where τ is shear stress, $\dot{\tau}$ and $\ddot{\tau}$ are the first, second derivative of shear stress with respect to time respectively, γ is shear strain, $\dot{\gamma}$ and $\ddot{\gamma}$ are the first, second derivative of shear strain with respect to time respectively, τ_s is shear yield limit, G_1 is shear elastic modulus, G_2 is viscoelastic shear modulus, η_1 is viscoplastic viscosity factor, η_2 is viscoelastic viscosity factor. Eq. (4) is the stress-strain eq. of the five elements rheological model in the solid-liquid zone of Al-Si alloy.

The rheological parameters in the solidifying temperature zone of Al-Si alloy can be obtained from the experimental results. These parameters are listed in Table 1.

Table 1 The rheological parameters in the solid-liquid zone of Al-Si alloy

θ / ℃	G_1 / MPa	G_2 / MPa	η_1 / Pa.s	η_2 / Pa.s	τ_s / kPa
600	1.3	0.85	74.9	16.4	0.238
590	1.6	1.50	109.0	26.5	0.905
580	2.2	5.40	218.0	137.0	8.510

It can be concluded that these parameters are all the function of temperature. The relationships between the parameters and temperature may be obtained in the way of linear regression

$$X = \exp(A + BT) \quad (5)$$

where A and B all are constants. Then the stress-strain eqs. of Al-Si alloy in cases of any temperature can be gotten.

Isobe etc[4, 5] studied the relationship of the rheological model of Al alloy and the solid-liquid zone of alloy. For Al-Si hypoeutectic alloy, the solid-liquid zone can be divided into quasi-solid zone and quasi-liquid zone (Fig. 4). The quasi-solid zone was reduced and the quasi-liquid zone was amplified due to the increasing of the content of Si. The quasi-solid zone was approximate to zero (Fig. 5), while the content of Si is above 5%. The mechanical behaviors of alloy exhibited the liquid metal of Newton-viscid fluid. The rheological model of alloy can be simplified to Bingham body model

$$[H_1] - [S \mid N_1] \quad (6)$$

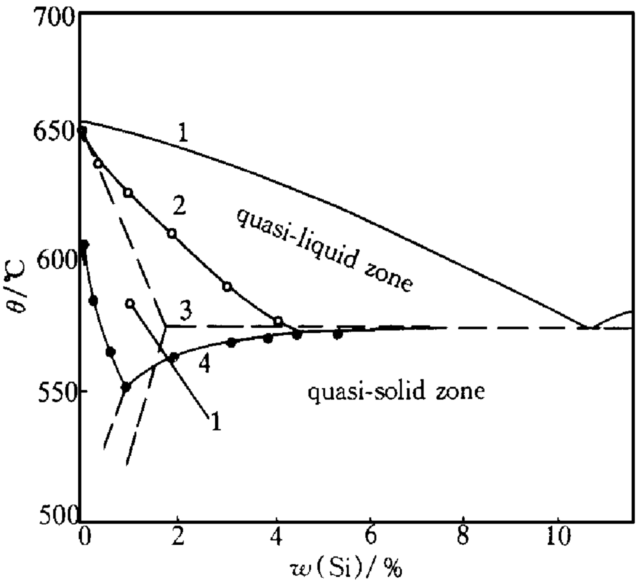

Fig. 4 Site of Al-Si alloy quasi-liquid zone and quasi-solid zone in phase diagram

1 —liquid line; 2 —quasi-solid line; 3 —solid line; 4 —real line

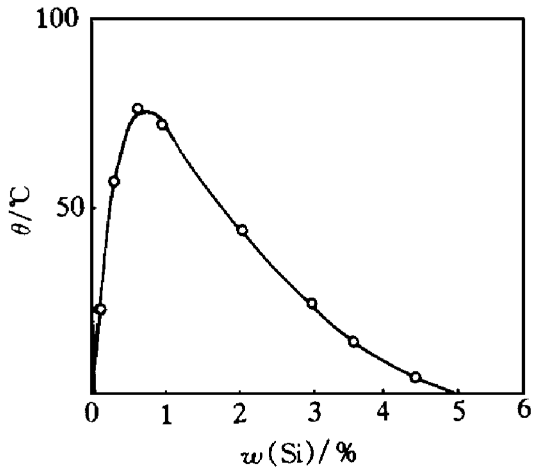

Fig. 5 Change regularity of Al-Si alloy quasi-solid zone with composition

The rheological behaviors in the solid-liquid zone can be analyzed from "loose connection" of solid dendrite. Quenching in the solid-liquid zone confirmed[6-8] that the connection of the dendrite occurs when the solid fraction g_s is above or equal to 25% in the solid-liquid zone and the solid-liquid state before full solidifying exhibits an understable transient dendritic framework — "loose connection" state. Because there was still a little non-solidifying liquid phase during grain boundaries and the interface connection force was much smaller than hyperelastic solid dendrite. While the outer load was very low, the connection of dendrite had very high elastic modulus, which made it exhibit almost rigidity on instantaneous load, without transient deformation. The elasticity after-effect phenomenon of dendritic framework exhibited during the stage of sustained load. On the countrary, if the load was very high, the dendritic framework would break, which changed an understability into a stability, hence it exhibited the process of elastoplastic and deformation at the time. When the load was sustained, the interface strength of the grain boundaries was still very low, then the interface could slip each other, and viscoplastic flow occurred. As the structure strength of alloy was very low in the solid-liquid zone, hence hot tearing took place easily due to the action of thermal stress and outer mechanical load. However, the liquid phase was limited during dendrites, it was hard to weld the hot tearing seam during dendrites. Thus, the solid-liquid zone may be the main temperature zone where solidification defects occurred easily.

4 CONCLUSIONS

(1) The rheological behavior of Al-Si hypoeutectic alloy in the solid-liquid zone may be described by the five elements rheological model

$$[H_1] - [H_2 | N_2] - [S_B | N_1]$$

The model may be simplified as Bingham body model when the content of Si is above 5%.

$$[H_1] - [S_B | N_1]$$

(2) The stress-strain eq. of Al-Si alloy are

$$\dot{\gamma} + G_2 \eta_2 \gamma = \frac{1}{G_2}\dot{\tau} + \frac{(G_1 + G_2)}{G_2 \eta_1} \qquad \tau < \tau_s$$

$$\ddot{\gamma} + \frac{G_2}{\eta_2}\dot{\gamma} = \frac{1}{G_1}\ddot{\tau} + \left(\frac{1}{\eta_1} + \frac{1}{\eta_2} + \frac{G_2}{G_1 \eta_2}\right)\dot{\tau} + \frac{G_2}{\eta_1 \eta_2}(\tau - \tau_s) \qquad \tau > \tau_s$$

(3) The rheological parameters of Al-Si alloy in the solid-liquid zone increase with the decreasing of temperature. As the content of Si is above 5%, the rheological parameters and the temperature are related by the function

$$X = \exp(A + BT)$$

(4) The behaviors of "loose connection" of solid phase dendrite confirm that the solid-liquid zone may be the important zone of occuring of solidifying defects, it is worth deep studying in terms of microrheology.

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