Rheologic behaviors of A356 aluminum alloy billet produced by semisolid continuous casting process

*Shuming XING[1], Lizhong ZHANG[1], Yunhui DU[1], Daben ZENG[2], Jinlin TANG[2]
(1. Department of Mechanical Engineering, Beijing Jiaotong University, Beijing 100044, P.R.China;
2. Department of Mechanical Engineering, Tsinghua University, Beijing 100084, P.R.China)

Abstract: The experiments for rheologic behaviors of semisolid continuous casting billets of A356 alloy in semisolid state had been carried out with a multifunctional rheometer. The results show that the deformation rate increases with loading time, the maximum strain reaches to 120 % (which is one time larger than that of traditional mold casting billet) and the strain can be rapidly eliminated to 10% after unloading. Moreover, there is a critic stress for billet deformation even in semisolid state, which is named as critic shear stress. This stress increases with the decreasing of heating time. The rheologic behaviors can be expressed by five elements mechanical model (H_2 - [N_1|H_2] - [N_2|S]) and can be modified with the increasing of heating time.

Keywords: semisolid continuous casting; billet; aluminum alloy; rheologic behavior

1. Introduction

Semisolid continuous casting is a new and effective method to produce the billets for semisolid processing. It has been used overseas[1]. Recently, in China, many researches focus on this method to promote its application in industry, and several kinds of semisolid continuous casting machines have been developed to produce aluminum alloy and steel billets for semisolid processing[2~4]. It can be desired that these machines will be quickly equipped in industry in the near future. So many manufacturers are eager to know the rheologic behaviors of continuous casting billet.

Although the experiments and researches about deformation behaviors of the billets, made by Ospray, Cycle-temperature, and Liquidus-pouring and so on, have been carried out before, and their rheologic models have been obtained[5~7], the reologic behaviors of continuous casting billet are still not clear. Nevertheless, these behaviors are very important for the industrial application and the development of semisolid continuous casting technology as well as its products. Therefore, in this paper, an experimental study on the rheologic behaviors of semisolid continuous casting billet was carried out under the static condition.

2. Experimental

2.1 Sample and equipment

In order to compare the rheologic behaviors of the billets produced by different methods, several samples were cut from the billets produced by Ospray method, traditional mold casting and semi-solid continuous casting, respectively. The dimension and shape of the sample (a disc with 20mm in thickness and 57 mm in diameter) are shown in Fig.1.

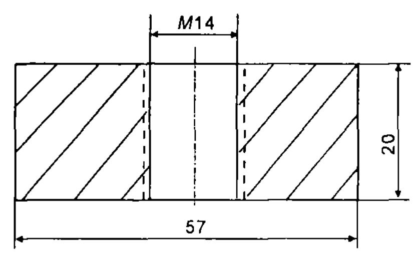


Fig.1 Shape and dimension of sample

Experiments to measure the rheologic behaviors of the billets were carried out with a multifunctional rheometer shown in Fig.2[8]. The working principle is shown in Fig.3.

Fig.2 Testing equipment

The sample at some semisolid temperature was synchronously loaded a pressing force by a press plate and a

*Shuming XING: Doctor, Professor, major research in material forming process.
Tel: +86-10-51682036
E-mail: smxing@center. bjjtu. edu. cn

tension force by a withdrawal bar, therefore in the center part of the sample a shear stress was produced by the couple forces. Under shear stress, deformation occurs. The displacement inducers were set on the withdrawal bar to pick up the deformation values, and a data collection equipment records and transfers the information of time and deformation so as to obtain the rheologic curve.

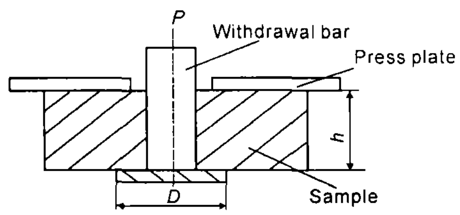


Fig.3 Principle of rheologic shear test

2.2 Test condition and procedures

The test procedures were as follows. Firstly, the sample was assembled with the withdrawal bar and the pressing plate (as shown in Fig.3). Then, the assembled sample was put into a stove with a multifunctional rheometer and heated to some temperature at which the sample will be hold for some time. Finally, the sample was loaded to make some deformation.

The experiments were divided into two groups. One was in a constant load 600 g for 600 s to measure deformation curves; the other was in different load for 600 s. In order to eliminate the effects of the residual deformation from previous ones, new tests should be set to start after holding another 600 s.

In order to study the effect of load on semisolid deformation, a series of loads were placed on the sample under a constant heating temperature and holding time, and rheologic curves were obtained. Moreover, in order to know the effect of holding time on the deformation of semisolid continuous casting billets, a series of holding times of 1 800 s, 2 400 s, 3 000 s, 3 600 s, 4 200 s, 4 800 s, 5 400 s were selected under a constant temperature, and rheologic curves versus variable holding times were obtained.

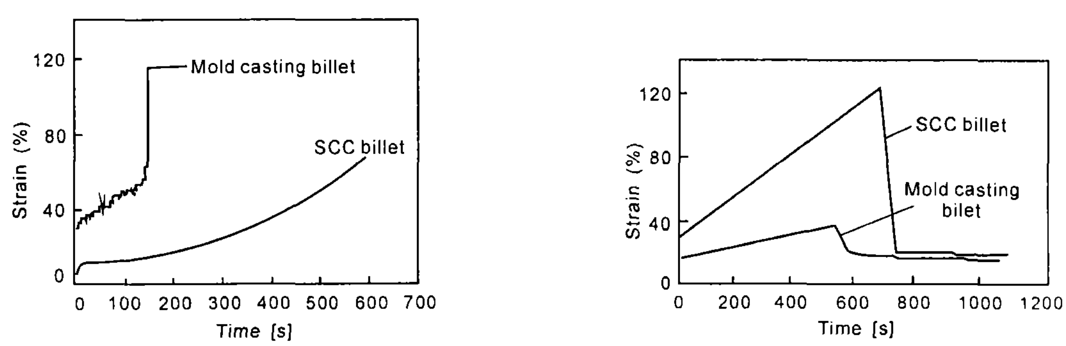
3. Results

3.1 Comparison of deformation between different billets under a constant load

Compared with the deformation curves of the billets produced by traditional mold casting and semisolid continuous casting, it can be seen that there is a large difference between them (as shown in Fig.4). The billet produced by the semisolid continuous casting can bear over 100 % deformation without breaking, while the billet produced by traditional mold casting can only bear 50 % ~ 60 % deformation. More interesting phenomenon is that the remained deformation after unloading is only 10 %, even the deformation under loading is very large. The larger the deformation under loading, the faster the recovering rate.

The rheologic curves of loading versus deformation can be divided into two segments. One is the beginning period in which the deformation increases linearly with loading time. The other is the following period in which the deformation rate decreases and the deformation still increases linearly or conically with loading time. From the rheologic curve, it is believed that there exists the Hook Body and Newton Body in the rheologic mechanical model.

Moreover, the rheologic curves during unloading period include a linear curve and a level curve. The slope of linear curve gives the recovering rate, and the height of the level curve gives the remained deformation. From Fig.4b, it can be seen that the recovering rate of semisolid continuous casting billet is faster than that of traditional mold casting billet, and this remained deformation is almost the same.



(a) Loading period

(b) Loading and unloading period

Fig.4 Rheologic curves during the loading and unloading process (SCC: Semisolid Continuous Casting)

In addition, there exists maximum deformation over which breaking occurs, no matter that the load is large or small for common continuous casting billets. This maximum deformation of traditional mold-casting billet is only about 60 %. However, as shown in Fig.5, the rheologic curve of the Ospray sample during loading period is gibbous not concave like that of semisolid continuous casting billet. This means that the deformation rate decreases with loading time. If the loading time is long enough, the strain may become constant or the deformation may stop. During unloading period the curve is slower than that of semisolid continuous casting billet and has not obvious level segment. All of these show that the rheologic curves of the billets produced by different methods are obviously different.

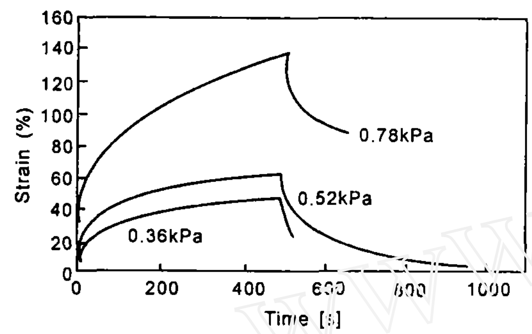


Fig.5 Rheologic curves of billet produced by Ospray[9]

3.2 Effect of holding time on rheologic curve

It is seen from Fig.6, that the rheologic curve of semisolid continuous casting billet is influenced by holding time, even the loadings are the same. For holding time 2 400 s under the loading 600 g, the deformation is increased slowly with loading time, and reached a maximum value 6.5 % some time later. The deformation is slowly recovered and the remained deformation after unloading is about 1.5 %. However, the maximum deformation during loading period and the remained deformation after unloading are quite different while holding time is prolonged. For example, the maximum deformation for holding time 3 600 s increases to 60 %, which is 10 times larger than that for holding time 2 400 s.

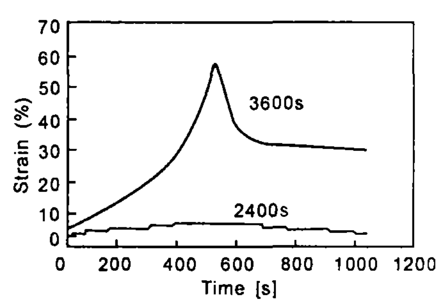


Fig.6 Influence of heating time on curves

3.3 Rheoelogic properties under different loadings

Compared with the two curves in Fig.7, it can be seen that the deformation rate is mainly influenced by the loading. Even though the difference of loadings is only 50 g, when holding time reaches to 600 s, the deformation under the loading 350 g increases one time, i.e., the larger the loading, the greater the deformation rate.

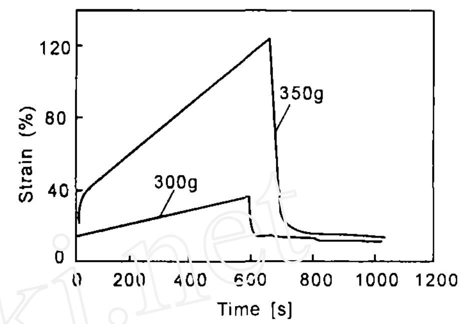


Fig.7 Influence of loading on curves

In addition, it is found that the deformation of semisolid continuous casting billet is insignificant when the loading is smaller than 200 g. This shows that there is a critic stress. Only when the actual stress is larger than this stress, the deformation may occur significantly. So it is believed that a St. Venant body is included in the rheologic mechanical model of semisolid continuous casting billet.

The critic stress can be calculated by the following formula:

$$\tau = \frac{pg}{A} = \frac{pg}{\pi DH} \tag{1}$$

Where τ——Shear stress [Pa]
p——Loading [kg]
A——Shear deformation area [m]
H——Sample height [m]
D——Diameter of the shearing column [m]

For formula (1), the critic stress is greatly related with holding time. When the holding time is smaller than 1 800 s, the critic stress is 4.5 kPa. However, when the holding time is prolonged to 3 600 s, the critic stress decreases to 2 kPa. When the holding time is longer than 3 600 s, the critic stress fixes at 2 kPa.

4. Discussion

4.1 Rheologic model of semisolid continuous casting billet

To sum up, it can be obtained that the characteristics of semisolid continuous-casting billet of aluminum alloy:

(1) Instantaneous shear strain is seen after loading and instantaneously recovering shear strain is seen after unloading in the experiments. These phenomena confirm that there is a lone Hook Body in the rheologic model.

(2) There is a pre-efficiency of elasticity during loading and back-efficiency of elasticity during unloading

in the rheologic curves. So it is believed that there is a Kelvin Body in series in the mechanical model.

(3) The fact that there exists a critic stress confirms that there is probably a St. Venant Body connected in the mechanical model.

From the above characteristics of the rheologic curves, the mechanical model may be described by a five-parts as follows: $H_2 - [N_1 | H_2] - [N_2 | S]$, see Fig.8

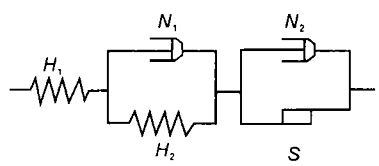


Fig.8 Mechanical model of billet produced by semisolid continuous casting

This model agrees with that of the billets with degenerate dendritic structure[9], and differs from that of the Ospray billets with global structure, which is described by a six-parts model[9]. The reason is that there are many degenerated dendrites besides some globule particles in the semisolid continuous-casting billets (as shown in Fig.9).

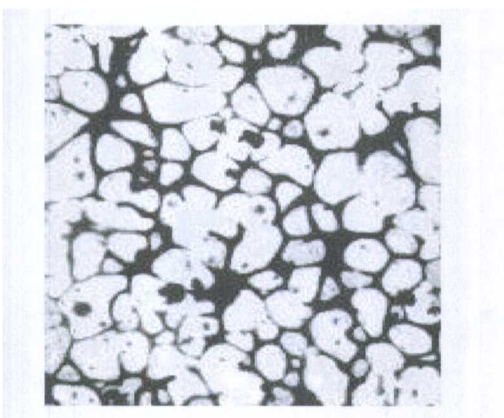


Fig.9 Microstructure of semisolid continuous casting billet

4.2 Critic stress of semisolid continuous casting billet

Existing a critic stress at the semisolid state is a prevalent phenomenon to the billets with non-dendritic microstructure. The value of the critic stress is related to the microstructure of billets and the heating process. The larger the ratio of non-dendritic grain in original structure, the smaller the critic stress. The longer the holding time in heating process or the higher the heating temperature, and the smaller the critic stress.

Critic stress is the basis to select the semisolid processing machine. The larger the critic stress of the billet, and the bigger the machine.

4.3 Influencing factors on rheologic curve

The loading and the holding time has important effects on the rheologic properties of semisolid continuous casting billet. It is easy to understand that the effect of loading on the rehologic properties is mainly dependent on the deformation rate when the loading is larger than the critic stress. However, the effect of the holding time on the rehologic properties is quite different from that of other researches. In the past, it was believed that the holding time should be as short as possible in order to prevent the microstructure from being coarsen[8]。 Whereas the results here show that increasing the holding time can modify the deformation ability and is beneficial to the semisolid forming process. The reason resulting in this difference in the rheologic properties is that the original microstructure of continuous-casting billet is different from that of the billets produced by Ospray and other methods. It is proved that the microstructure of billet changes during the holding time at semisolid temperature. Three morphology evolutions such as dendrite's degenerating, particle grain's spheroidization and globule grain's Oswarld ripening[5] happen, and these three morphology evolutions are of dynamical process. Therefore, the longer the holding time lasts and the more sufficient the evolution is.

Because of the high productivity of semisolid continuous casting process, the grain of billet is not near-sphericity. In fact, there are three kinds of grain morphologies: sphericity, particle and degenerated dendrite (as shown in Fig.9). The dimension of the sphericity is only 20～40 μm, which is easy to occur Ostwald ripening. The shape of the particle grain is mainly near-sphericity. This particle grain transfers into sphericity step by step during the holding time. Especially, the degenerated dendrite may change into particle or sphericity during the holding time. So the rate of sphericity in microstructure increases with the holding time, and the critic stress decreases with the holding time. On the other hand, in the microstructure of billet, there mainly exists fine sphericity just as the same as that of the billet produced by Ospray method. The changes of the holding time will result in grain coarsening which will decrease the rehologic properties. So it is suggested that the holding time should be as short as possible.

The result that the rehologic properties of the billet do not change badly with the increasing of holding time provides a great deal of convenience for industrial application.

5. Conclusions

The following conclusions about the reologic properties of the semisolid continuous-casting billet are experimentally obtained.

(1) The mechanical model is a five-unit mechanical model as $H_2 - [N_1 | H_2] - [N_2 | S]$

(2) The least critic stress is about 2 KPa.

(3) Deformation ability of the billets is modified with the increase of holding time at the semisolid temperature.

References

〔1〕 Shuming XING, Daben ZENG and Hanqi HU. Progress of the semisolid continuous casting technology 〔J〕. Foundry, 2000, (8): 449 (in Chinese)

〔2〕 Kui ZHANG. Application of semisolid process of aluminum alloy 〔A〕. Transaction of the 1st Conference of the Semisolid Metal Processing technology 〔C〕. Beijing, Apr. 2000 (in Chinese)

〔3〕 Weimin MAO. Research on forming and continuous casting billets of AlSi7Mg alloy 〔A〕. Transaction of the 1st Conference of the Semisolid Metal Processing Technology 〔C〕. Beijing, Apr. 2000 (in Chinese)

〔4〕 Shuming XING. Study of the semisolid continuous casting process of the iron and steel 〔D〕. Beijing: PHD Dissertation, University of Science and Technology Beijing, 1999 (in Chinese)

〔5〕 Mingfang ZHU. The fabrocation of ZA12 alloy with non-dendritic structure and morphology evolution of the primary phase 〔D〕. Nanjing: PHD Dissertation, Southeast University, 1995 (in Chinese)

〔6〕 Kuiling CHEN, Songyan ZENG, and Qingchun LI. A Experimental study on the rheologic behavior of the Al-Si alloy at the solid-liquid coexisting zone 〔J〕. Journal of the Harbin Institute of Technology, 1991, (1): 85~89

〔7〕 Hao ZHANG, Zhenghua CHEN and Zhitao KANG. Semisolid extrusion of mutilayer Ospray 6066 alloy 〔J〕. Transaction of Nonferrous Metals of China, 1998, 8 (2): 191~196

〔8〕 Chenglin CUI. Secondary heating method of semisolid Al-Si-Mg alloy in thixo-forming process 〔A〕. Transaction of 4th youth CMES 〔C〕. Beijing: Mechanical Industry Press, 1998 (in Chinese)

〔9〕 Jinlin TANG. Study on Rhologic Model of A356 Aluminum Alloy 〔D〕. Beijing: PHD of Tsinghua University, 2000 (in Chinese)