

Modified rheological processing technology and its applications in iron and steels

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Abstract: A traditional semisolid processing based on the rheological properties of semisolid alloy is very difficult in manufacturing the semisolid slurry because of the chase for spherical, fine and high solid fraction of the primary solid in the slurry. Through many experiments, it is found that it is not very necessary to excessively emphasize theglomeration and high solid fraction considering of the facts that the rheological properties of the semisolid slurry is controlled by not only the microstructure of the primary solid but also the rheological conditions. The manufacturing slurry can be simply regarded as preparing the semisolid alloy melt, therefore, a modified semisolid processing technology is presented. Its procedure consists of three basic steps, such as preparing slurry, filling mould cavity and solidification with pressure. The basic aim of the preparing slurry is to obtain the slurry containing 5%–20% (volume fraction) primary solid with particle or stick instead of spherical morphology. The experiment results show that, with the modified rheological processing technology, many steel and nonferrous alloy products are industrially produced.

Key words: semisolid alloy; steel; rheology processing; slurry; squeeze casting; solid fraction

1 Introduction

In the past 40 years, in the development of semisolid processing technology, a lot of the researches focused on manufacturing the semisolid slurry because of the expectation for spherical, fine and high solid fraction of the primary solid in the slurry. However, there is few suitable methods to industrial applications though many methods were presented and experimentally used, especially for iron and steel[1–2].

After many experiments, it is found that it is not very necessary to excessively emphasize on theglomeration and high solid fraction for that the rheologic properties of the semisolid slurry is controlled by not only the microstructure of the primary solid but also the rheological conditions. The manufacturing of the semisolid slurry can be simply regarded as preparing of the semisolid alloy melt, therefore, a modified semisolid processing technology is presented in the paper. Its procedure consist of three basic steps, such as preparing slurry, filling mould cavity and solidification with pressure. The basic aim of preparing slurry is to obtain the slurry containing 5%–20% (volume fraction) primary solid with particle or stick instead of spherical morphology. With the modified rheology processing

technology, many steel and nonferrous alloy products are first industrially produced using rheological technologies, such as hammers made of high manganese steel and high chromium cast iron, double ears linker made of alloy steel, carburetor body made of A356 aluminum alloy, valves body made of alloy steel.

2 Rheological properties of semisolid alloy slurry

2.1 Theoretical model of apparent viscosity and its influencing factors

The outstanding advantages of the semisolid processing based on the material rheology are resulted from the excellent rheological properties integrated the fluidity in liquid states with the plasticity in solid states. It is proved experimentally and theoretically that the rheological properties of alloy slurry is consumingly controlled not only by the microstructure of the slurry, but also by the rheological conditions, such as shearing rate, shape and dimensions of the mold cavity, shearing stress. In the traditional opinions of semisolid processing, the primary solid in the alloy slurry should be fine spherical particles. Therefore, the manufacturing process is complicated, costly and difficult.

Apparent viscosity is usually used to express the

rheological properties of the alloy slurry. A theoretical model of the apparent viscosity as shown in Formula (1) is built by LIU and XING[3] based on energy dissipation theory.

$$\eta_a = \left[\frac{(\lambda_f + \lambda_j)V_f^3 \rho}{2l} + \sqrt{\frac{3}{\pi}} \frac{\rho_s f_s v_f^3}{d(1-f_s/f_{sm})^{5/2} f_s} + 4\pi\eta_0 V_{LS}^2 \beta \right] \dot{\gamma}^{-2} \quad (1)$$

where λ_f and λ_j are frictional and local energy dissipation factors respectively; V_f is the fluctuation velocity of the solid in the slurry to describe the turbulence trends; V_{LS} is the relative flow rate between liquid and the solid in the slurry used to describe the separating trends of the two phases; V_{LS} is the relative velocity between liquid phase and solid particles; ρ and ρ_s are densities of slurry and solid particles respectively; l is the length of a running route; d is the mean particle diameter; f_s is the primary solid factors; f_{sm} is the critical solid fraction, $\dot{\gamma}$ is the shearing rate of the slurry; η_0 is the viscosity of pure liquid; β is an varying parameter which is rising from 0.1 to 0.3 with the increase of the solid fraction f_s and with the decrease of the diameter d of the primary solid particle in the slurry.

From Formula (1), the influencing factors can be summarized in two kinds. One is of the semisolid slurry, the other is of the rheological conditions. The factors of the rheological conditions include the length l of a running route, the diameters D of the route, the energy dissipation coefficient λ_f along the running passage, the partial energy dissipation coefficient λ_j , where

$$\lambda_f = \frac{64\eta_0}{\rho DV} \cdot \frac{l}{D}$$

and the shearing rate $\dot{\gamma}$ of the slurry. From Formula (1), the effects of these factors are prominent on the apparent viscosity. Especially, the shearing rate influences apparent viscosity with an exponential rule, which is consentaneous with the power law[4].

The other kind factors influencing the apparent viscosity are of semisolid slurry, such as the liquid viscosity

$$\eta_0 = K \exp(E_0 / RT)$$

where K is a constant; E_0 is flow activation energy; R is the gas constant; T is the temperature; ρ and ρ_s are densities of liquid and primary solid, respectively; f_s and d are the solid fraction and the diameter of the primary solid particle in the slurry. The effects of the shape coefficient ϕ of the primary solid particle are exhibited as Formula (2) through the critical solid fraction f_{sm} when the slurry loses its fluidity.

$$f_{sm} = -0.1132\phi^2 + 0.4164\phi + 0.5211 \quad (2)$$

2.2 Effects of solid microstructure on apparent viscosity

In order to concisely compare the influencing extents of the primary solid factors f_s , d and ϕ on the apparent viscosity of semisolid slurry, a calculation in the general value ranges of various factors can be done by substituting the minimum and maximum values of them, respectively, into Formula (1). The calculated results are shown in Table 1. It is seen that the solid fraction f_s has the most effect on the apparent viscosity, the solid diameters d takes the second place. When both of them vary, the apparent viscosity varies very large. However, the apparent viscosity varies with the shape coefficient by only about 15% when the primary solid changes from a short bar ($\phi=0.5$) into a spherical particle ($\phi=1.0$).

Table 1 Effects of solid microstructure on apparent viscosity of semisolid slurry

Factor	Solid fraction	Solid diameter/ μm	Shape coefficient
Minimum value	0.2	20	1
Maximum value	0.5	100	0.5
Apparent viscosity	About 1000%	About 500%	About 15%

Based on the above calculation and many experimental results[5], the shape of the primary solid in the slurry cannot make apparent viscosity vary excessively, it is not necessary to chaseglomeration of the primary solid particle in the semisolid slurry.

From Formula (1) and Table 1, one can see that the diameter of the solid particles in the semisolid slurry has obvious effects on the apparent viscosity—apparent viscosity decreases with the increase of the diameters of the solid particle. Although this result is against the traditional view that fine solid particle is beneficial to the semisolid processing[8–10], it is easy to understand considering the increase of the solid-liquid interface area with the decrease of the solid diameter. In fact, the fine solid mainly show the mechanical properties of the alloy rather than the rheology of semisolid slurry.

The effects of solid fraction of the alloy slurry on the apparent viscosity shown in Formula (1) are easy to accept. However, the traditional semisolid processing chase to high fraction in order to enhance the mechanical properties of the products formed. This inconsistent requirement results from the traditional processing with semisolid billet rather than the semisolid slurry. Many experimental results shows that the critic shearing stress increases tempestuously with the solid fraction increasing, especially when the fraction is larger than 0.4.

From the above analysis, in order to obtain seemly rheologic properties, it is not necessary to chase fine,glomerated and high fraction of the primary solid

in the semisolid slurry manufacturing process. Because there are many inevitable factors, such as high pressure, high cooling rate and lower pouring temperature, to modify the mechanical properties of the products, it is also not necessary or not economic to chase fine,glomeration and high fraction of the primary solid in the semisolid slurry manufacturing process. This viewpoint benefits to accelerate the industrialization of the semisolid processing.

3 Modified rheology processing technology

Based on the above viewpoint, a modified rheological processing named general semisolid processing is presented in which the proper rheology and satisfied mechanical properties are created, respectively, in the slurry preparing and forming stages. The task of the slurry preparing is only to obtain proper rheology of the semisolid alloy, and the task of the forming stage is to obtain the required shape, dimension and inner quality. Because theglomeration of primary solid particles is not necessary, any simple method, such as controlled casting temperature or slope cooling, can be used to prepare the semisolid slurry as long as the primary solid particles in it is not continuous network or developed dendrite, in which the slurry can be filled and formed well in the condition of pressure. Moreover, the traditional casting and forging equipments, such as die casting machine and mold forging machine, can be used to make the slurry formed.

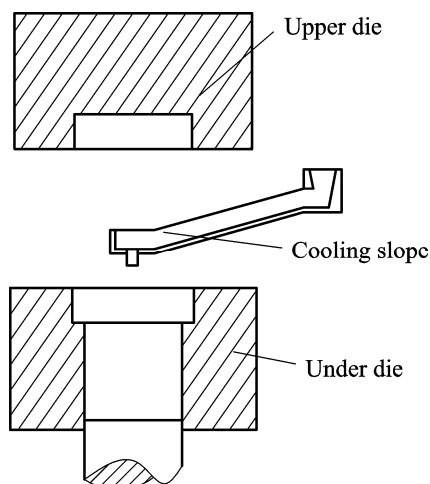


Fig.1 schematic diagram of semisolid rheological process

In fact, a modified rheological processing technology—semisolid rheologic casting was presented in 2001[11]. In the process, there are three steps: preparing slurry by slope cooling method, filling die cavity by pressure, solidification and compacting by pressure. The main equipments used in the process are a slope with temperature control, a permanent mold made of metals and a pressing machine used to supply pressure,

which are shown in Fig.1. According to the forming machine, the process can be divided into three branches: semisolid rheo-squeeze casting, semisolid rheo-die casting and semisolid rheo-die forging.

In the semisolid rheo-squeeze casting process, the alloy melt is first poured into the cooling slope, the semisolid slurry is obtained when the alloy melt flows through the slope and directly flows into a permanent mold set in the squeeze casting machine. And then, a pressure is supplied to the slurry and make it fully fill the mold, finally increased pressure makes the slurry solidified and compacted.

Similarly in the semisolid rheo-die casting process, the alloy melt is first poured into the cooling slope and it becomes semisolid slurry when it flows through the slope, and then the slurry directly flows into the pressure chamber connected with the die, finally a pressure is supplied with the die casting machine to the slurry and make it filled into the die and solidified and compacted. This process has been used industrially by FAN et al[12].

In the semisolid rheo-die forging process, the alloy melt is also first poured into the cooling slope, the semisolid slurry is obtained when the alloy melt flows through the slope and directly flows into a forge mold set in the forging machine, and then a pressure is supplied to the slurry and make it fully fill the forge mold, finally an increased pressure makes the slurry solidified and compacted.

In the semisolid rheological processing, preparing the slurry with a cooling slope is a common and key link. In order to ensure the semisolid slurry flow into the mold or pressure chamber under the gravity, controlling temperature method has to be used to ensure the slurry containing primary solid less than 20%. Thus, the slope must have a proper temperature which differs from different alloys, which is generally 100–200 °C, lower than the liquidus temperature.

4 Some applications of semisolid rheological processing of steel

4.1 Wear-resistant iron and steel

Hammer used in a crusher is a kind of wear resistant product. In the traditional production, the hammer is produced by gravity casting. However, its life is short because of some casting defects, such as shrinkages, porosity or cracks. Using the semisolid rheo-squeeze casting to produce the hammer is a successful selection. The hammer is made of the high chromium cast iron which is melted in an electric induction furnace. The liquid high chromium cast iron with a temperature of 1400 °C is poured into the upside of a cooling slope. The cooling slope with a pitch of 20°–45° and a temperature of 1100–1200 °C is used to prepare the semisolid slurry, in which the solid fraction is in the range 5%–20%. A vertical squeeze casting machine with the maximum

pressing force of 8 MN is used to make the slurry solidified and compacted, which can provide a 80 MPa pressure to the slurry. The hammer obtained with the modified technology is shown in Fig.2. Although the primary solid particle in the hammer is short-bar shown in Fig.3 rather than the glomeration, it is industrially proved that the processing is carried out successfully without any defects and the service life of the hammer produced by the semisolid rheo-squeeze casting is longer near by one time than that of the hammer produced by the traditional casting.

Similar results are obtained using the semisolid rheo-squeeze casting to produce the hammer made of the high manganese steel ZGMn13. Its life is 50% longer than that produced by sand casting.



Fig.2 Hammer produced by semisolid rheo-squeeze casting process

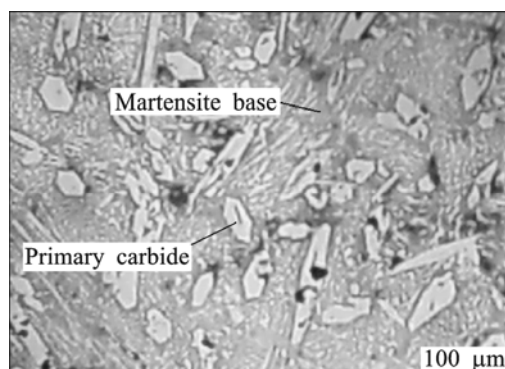


Fig.3 Microstructure of high chromium cast iron hammer

4.2 Carbon steel and lower alloy steel

Using the semisolid rheo-squeeze casting process, a pedestal of the carbon steel ZG230-450 is produced successfully, as shown in Fig. 4. Here, the pitch of the cooling slope is 30°–45°, the pouring temperature is about 1550 °C, the slope temperature is in the range of 1200–1300 °C, the pressure acted on the slurry is 80–120 MPa supplied by a squeeze casting machine with the pressure force of 5 MN. Although the primary solid is not of desired glomeration, as shown in Fig.4, the semisolid processing is not difficult. The pedestal obtained is smooth and compacted at the hot spot. Its mechanical properties are obviously higher than those of the pedestal produced by the traditional investment casting and σ_b reaches 700MPa and $\sigma_{0.2}$ reaches 500 MPa, as shown in Table 2.

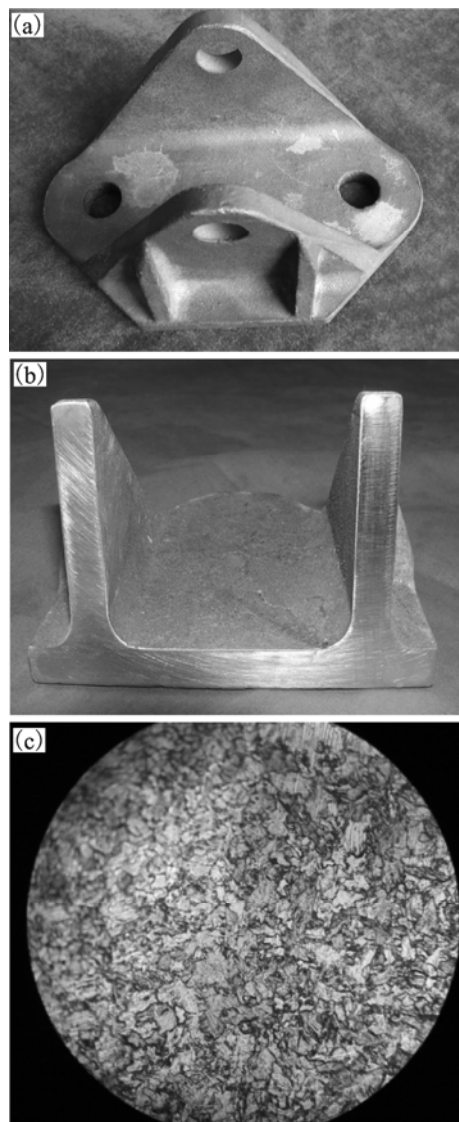


Fig.4 Pedestal produced by semisolid rheo-squeeze casting process

Table 2 Mechanical properties of steel ZG230-450

Process	σ_b /MPa	$\sigma_{0.2}$ /MPa	Total extension/%
Semisolid rheo-squeeze casting	600–700	530–580	11
Investment casting	500–550	250–280	25

Using the semisolid rheo-squeeze casting process, the journal box body and a gear of lower alloy steel are produced successfully. Here, the squeeze casting machine with the maximum press of 1 MN can supply a pressure of 100 MPa to the semisolid slurry, the temperature of the cooling slope with a pitch of 30°–50° is in the range of 1200–1300 °C. The products obtained have a smooth surface, accurate dimensions and compacted internal quality, as shown in Fig.5. The mechanical properties are also higher than those of the parts the produced by the traditional casting.

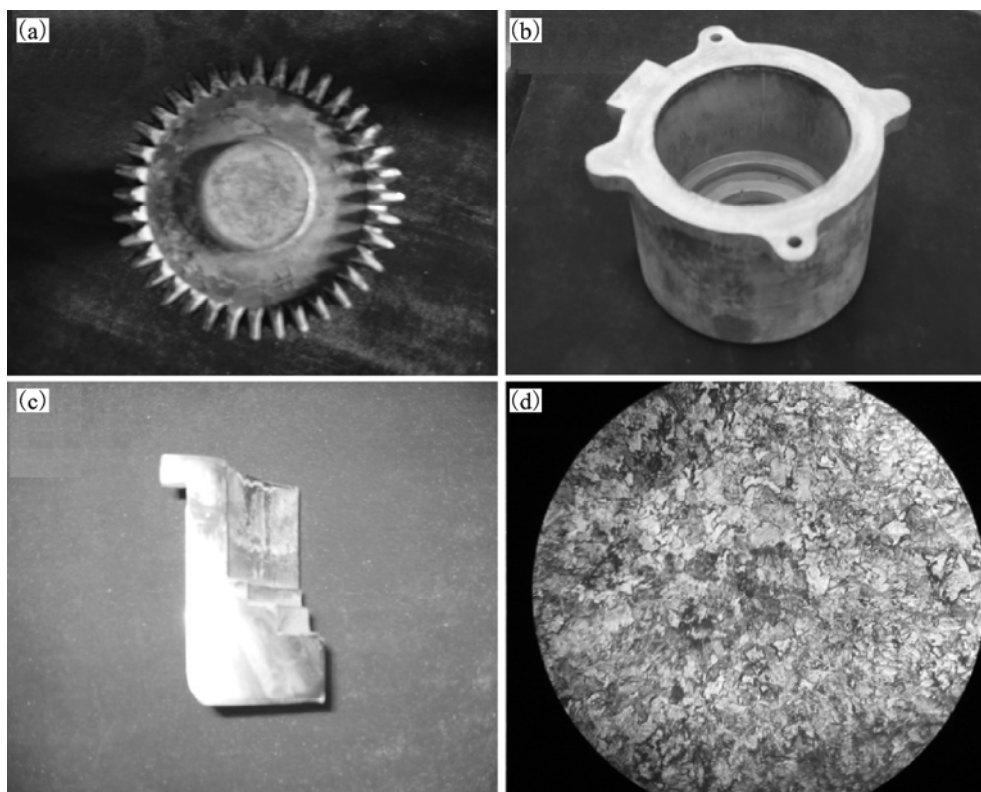


Fig.5 Gear and journal box body produced by semisolid rheo-squeeze casting process

5 Conclusions

1) The fine, glomerated and high fraction of the primary solid is not necessary in the modified semisolid rheological process, therefore, the semisolid slurry can be prepared by the simple cooling slope method, and the forming machine may be squeeze casting machine, die casting machine or die forging machine. Accordingly, the process is named semisolid rheo-squeeze casting, semisolid rheo-die casting and semisolid rheo-die forging, respectively.

2) The semisolid rheological process can be used to industrially produce fine quality products of alloys, especially iron and steels.

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