[Article ID] 1003- 6326(2001)03- 0409- 04

Relationship between solid fraction and distribution of Pb in Al-Pb ingot ①

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[Abstract] The influence of solid fraction of Al-28Pb alloy mushy on distribution of Pb in Al-Pb ingot was studied. The special electromagnetic stirring apparatus was used to prepare Al-28Pb alloy mushy and the relationship between solid fraction and stirring temperature was gotten. The results show that when solid fraction of Al-28Pb alloy mushy is less than 45%, Pb precipitation usually happens in the ingot. However, Pb precipitation in casting reduces gradually with increasing solid fraction of mushy, and when solid fraction is larger than 45%, Pb precipitation in casting can be removed.

[Key words] Al-28Pb alloy; solid fraction; stirring temperature; alloy mushy
[CLC number] TD 146.2 **[Document code]** A

1 INTRODUCTION

Al-Pb hypermonotectic alloy is a new type bearing material[1]. Great emphasis has been put on it especially since 1990s[2~4]. Pb has excellent lubricating property which can match that of Sn, but its cost is much lower than that of Sn, so Al-Sn alloy is replaced by Al-Pb alloy in the field of steel-backed bearing[5]. In Al-Pb alloy lubricating layer, if Pb particles distribute evenly in Al base, Pb can play a lubricating role at the whole contact surface and remove the abrasion of Al base, and the friction heat can be conducted by Al base rapidly. Otherwise, if Pb particles distribute in Al base unevenly, in Pb-rich region, Pb can play a lubricating role, but in Pb-lean region, Al can be worn fast, and this means the short life of the bearing. Therefore the distribution of Pb in Al base is very important for Al-Pb alloy.

Pb and Al are two kinds of metals with very different physical parameters, especially density and melting point. The density of Pb (11.3 g/cm^3 is much larger than that of Al (2.7 g/cm^3) and the melting point of Pb (327 ℃) is much lower than that of Al (660 ℃)[6]. In addition, in order to get perfect lubricating property, the content of Pb must be more than 10%[7], but the solubility of Pb in Al base is very small (less than 0.05% at 327 ℃), so gravity segregation of Pb always occurs in Al-Pb alloy by conventional casting[8]. In order to get Al-Pb alloy with uniform distribution of Pb particles, the better way at present is powder rolling process which include powder manufacturing, powder rolling, etc[9]. But it has too much working operations and wastes too much energy, so the cost of the product is very high.

In order to reduce the gravity segregation of Pb in casting at lower cost, Al-Pb alloy mushy was used to conduct casting for the first time. In this work, the influence of solid fraction of Al-28Pb(mass fraction, %) alloy mushy on Pb precipitation in the ingot is researched, and the relationship between solid fraction and size of Pb particle in precipitation zone is determined.

2 EXPERIMENTAL

The materials used in this work were industrial pure Al and Pb.

The experimental procedures were as follows.

1) Prepare Al-28Pb alloy liquid. The temperature of alloy liquid was 700 ℃(the ideal point of pouring for Al-Pb alloy ingot). The liquid must be degassed, and in order to remove the gravity segregation of Pb, it must be stirred sufficiently.

2) Prepare Al-28Pb alloy mushy. Fig. 1 was the schematic diagram of Al-28Pb alloy mushy-making apparatus. It included three main parts such as electromagnetic stirrer, uniform device and graphite crucible. Electromagnetic stirrer was made up of three couples of electric poles which distributed around the crucible evenly. Its main action was to break up the arborescent crystal in the process of solidification by circular motion of the mushy. Its power was 10 kW. Uniform device was a specially-designed fluid direc-

① [Foundation item] Project (715- 009- 060) supported by the Advanced Technical Committee of China; supported by China and Tsing-zhongde Postdoctoral Science Foundation [Received date] 2000- 06- 05; [Accepted date] 2000- 09- 21

tor. It could be moved up and down by using a assistant electric device. Its main action was to change the centrifugal flow and gravity segregation of Pb to get Pb-distributing-uniformly Al-28Pb non-arborescent mushy. Graphite crucible was a temperature-adjusting container. There were holes in its wall evenly. These holes contained heaters and coolers so as to adjust the temperature of the alloy mushy. There was a hole at the bottom of the crucible. Its action was to let out the alloy mushy.

The process of making alloy mushy was as follows. Preheat the crucible up to 550 ℃ by using the heaters in the heating pipes. Pour the 700 ℃ alloy liquid into the crucible. Overlay the upper cover. Inlet Ar gas through the gas pipe in order to prevent the alloy from oxidizing. Switch on the electromagnetic stirrer and the uniform device. Pump the cooling mediator into the cooling pipe to cool the alloy to the required temperature. Switch on the heaters in the heating holes and adjust the current to keep the temperature stable. The precision of temperature was ± 0.5 ℃. After a certain time, the uniform mushy with required solid fraction could be made.

3) Casting the Al-28Pb alloy ingot. After the mushy being prepared, open the spigot and let out the alloy mushy into metal mold (the cooling speed was about 200 ℃/min). The shape of ingot was cylinder with a diameter of 100 mm, and a height of 200 mm.

4) In order to determine the gravity segregation of Pb, three samples cut from the places near the top, the midst and the bottom of the ingot were observed by stereoscan technique. From the difference of size of Pb particles, the precipitation of Pb could be known.

3 RESULTS AND DISCUSSION

3.1 Relationship between solid fraction and stirring temperature of alloy mushy

When the temperature of metal is lower than its melting point, arborescent crystal of metal can be generated and the proportion of this solid metal to the whole metal is called solid fraction[10]. Under the action of stirring, the arborescent crystal can be broken up and gradually change into solid globes or ellipsoids which distribute in the liquid metal uniformly[11]. So the metal become mushy. For Al-Pb alloy, the solidification range of 327~660 ℃ is rather large, so solid fraction of the mushy mainly depends on the stirring temperature, namely, when the stirring temperature is kept constantly, a certain solid fraction of the mushy can be obtained. In our experiments, in order to obtain the uniform mushy not only for the primary solid phase but also for Pb, the stirring time must be not shorter than 20min generally. The distribution of primary solid phase and Pb in alloy mushy and solid fraction are determined by using cold quenching method[12]. Through experiments, the relationship between solid fraction and stirring temperature of Al-28Pb alloy mushy is gained (as shown in Fig. 2) and the regression equation after theoretical regression analysis is

$$y = 1\,532 - 4.3t + 0.003t^2 \qquad (1)$$

where y is solid fraction, t is stirring temperature. The regression coefficient is 0.998 46, and this proves that regression Eqn. (1) builds a correct relationship between solid fraction and stirring temperature of Al-28Pb alloy mushy.

3.2 Relationship between solid fraction and size of Pb particle

The precipitation of Pb (under the action of gravity force) in Al-28Pb alloy can result in increasing of the size of Pb particle along vertical direction of ingot, and the maximum size may locate in the precipitation zone. So according to the difference of the size of Pb particles at different height of the ingot,

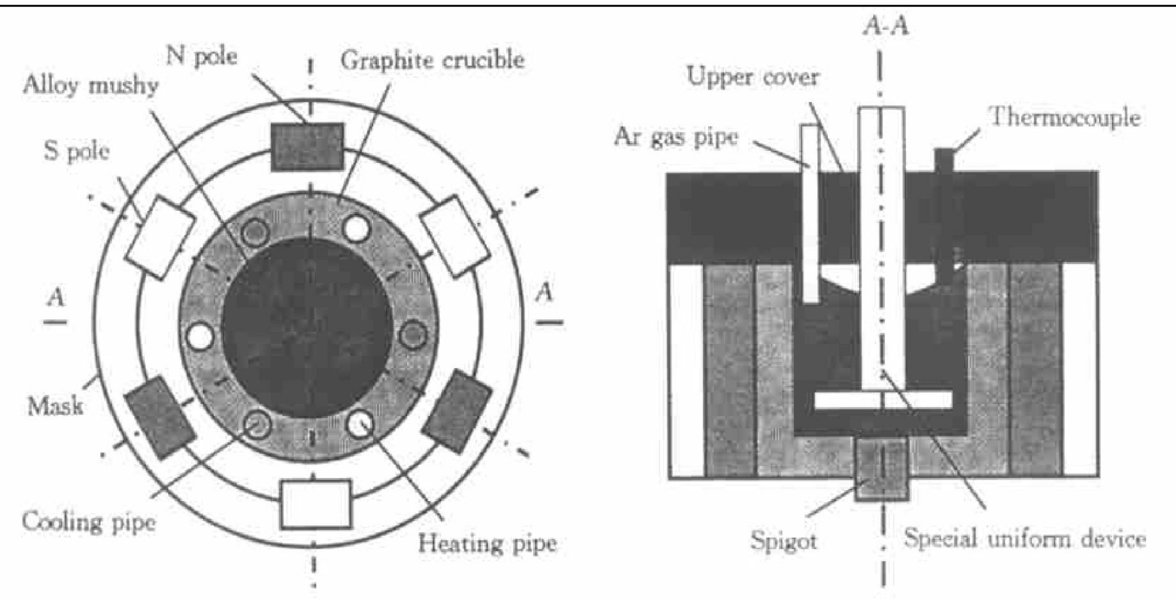

Fig. 1 Schematic diagram of Al-Pb alloy mushy-making apparatus

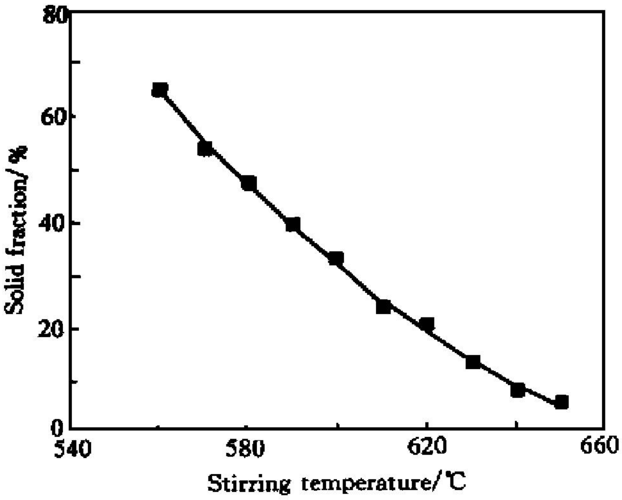

Fig. 2 Relationship between solid fraction and stirring temperature

we can know the situation of Pb precipitation in casting. When the difference of the size of Pb particles at different height of the ingot is removed, it can be said that the precipitation of Pb does not exist during casting. Through the experiments, the precipitation zone (at which the size of Pb particles is the maximum one) usually locates near the place 25 mm above the bottom of the ingot. So in order to study the influence of solid fraction on Pb precipitation, three samples were cut out of one ingot near the top, the midst and 25 mm above the bottom of the ingot respectively. The experimental data (which are the average values of the diameters of Pb particles) are shown in Fig. 3. It can be seen that with the increase of solid fraction of the mushy, the difference of the size of Pb particles at different height of the ingot reduces gradually, and when solid fraction is larger than about 45%, the difference of the size of Pb particles at different height of the ingot is removed. This shows that with the increase of solid fraction, the precipitation of Pb in casting can be removed gradually, and when solid fraction is larger than 45%, the precipitation of Pb can be removed basically.

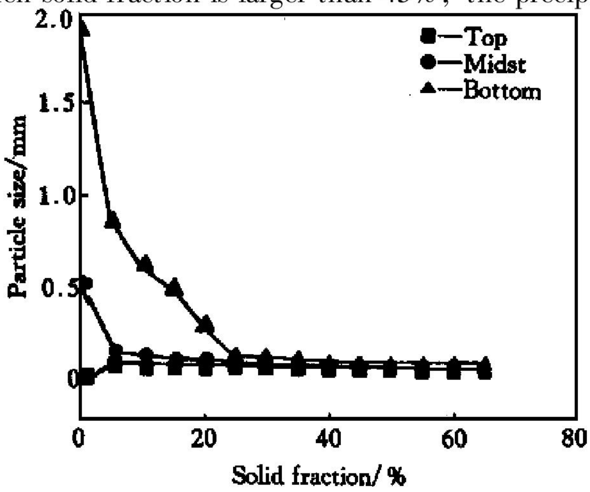

Fig. 3 Relationship between size of Pb particle and solid fraction

When solid fraction is larger than 45%, the relationship between solid fraction and size of Pb particles (the average value of the three values near the top, the midst and the bottom) is got after theoretical regression analysis. The regression equation is

$$x = -0.58y + 67.1 \quad (y \geqslant 45) \qquad (2)$$

where x is the average size of Pb particles, y is solid fraction. The regression coefficient was 0.984 32, and this proves that regression Eqn. (2) builds a correct relationship between solid fraction of Al-28Pb alloy mushy and size of Pb particle in the ingot when Pb precipitation in casting does not happen.

3.3 Discussion

In Al-28Pb alloy, since the solubility of Pb in Al base is very small, the most part of Pb exist in the form of particles. Because the density of Pb is much larger than that of Al and the melting point of Pb is much lower than that of Al, Pb particles after stirring can move to the bottom in Al liquid under the action of gravity force and gather together when they meet until they are surrounded by solid Al-Pb solution. Therefore when the solid fraction of alloy mushy is zero, that is, the alloy mushy is liquid (700 ℃), the size of Pb particles is zero (namely no Pb particles) on the top of the ingot and very large in the precipitation region near the bottom. Fig. 4 is the stereoscan photograph of the precipitation region of sample whose solid fraction is 0% (700 ℃, liquid). The dark phase is Pb, and the white phase is Al. It can be seen that the precipitation of Pb is very obviously.

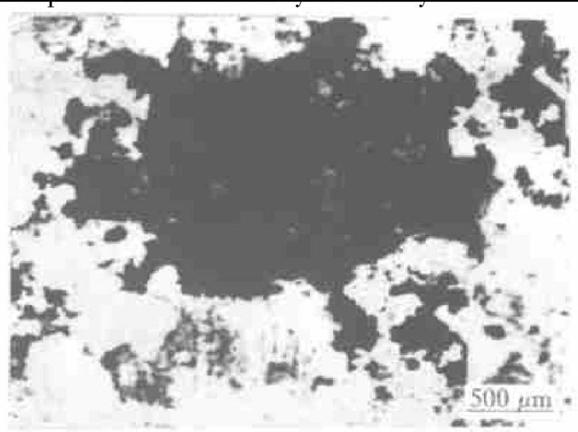

Fig. 4 Stereoscan morphology of precipitation region

When the solid fraction of alloy mushy is more than 0%, the primary solid Al particles distributed in the alloy mushy become the obstacles to the vertical motion of Pb particles, so the gravity segregation of Pb is restrained, and the difference of the size of Pb particles at different height of the ingot reduces continuously.

When the solid fraction of alloy mushy is about

45%, the liquid parts in the alloy mushy are almost surrounded by the primary solid Al particles and the precipitation of Pb can only be happened within the region of this small part of liquid. Because the distribution of the solid particles is uniform, the size of Pb particle is almost the same, and the difference of the size of Pb particles at different height of the ingot is removed. Furthermore, the larger the solid fraction, the smaller the volume of the surrounded liquid, so when solid fraction is more than 45%, with the increase of the solid fraction, the size of Pb particle is smaller and smaller, and they distributed uniformly in the ingot. Fig. 5 is the stereoscan photograph of the sample, whose solid fraction is 45%. The three photographs near the top, near the midst and near the bottom are almost same. The dark parts are Pb particles, the white parts are primary solid Al particles, and the dendritic parts are secondary solid phase. It can be seen that the distribution of Pb particles and the primary Al particles is relatively uniform, and the gravity segregation of Pb can be restrained.

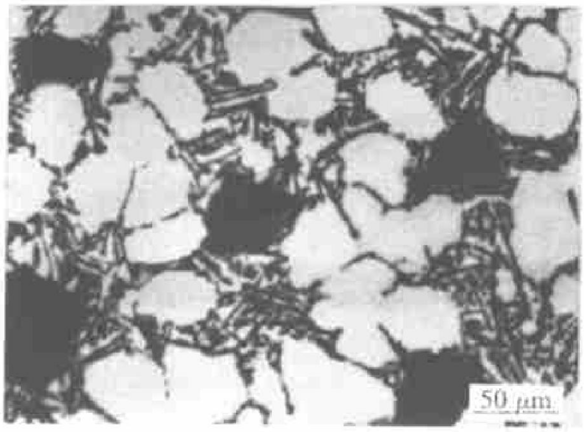

Fig. 5 Stereoscan photography of sample with solid fraction of 45%

4 CONCLUSIONS

1) Using alloy mushy to conduct casting is a new way to solve the problem of gravity segregation of heavy metal in hypermonotectic alloy casting. This method can be used to cast high quality ingot of Al-28Pb alloy simply, conveniently and economically.

2) For Al-28Pb alloy, the relationship between solid fraction and the stirring temperature of alloy mushy is

$$y = 1\,532 - 4.3t + 0.003t^2$$

where y is solid fraction, t is stirring temperature.

3) The extent of gravity segregation of Pb in casting reduces gradually with the increase of solid fraction of alloy mushy. When solid fraction of alloy mushy is larger than 45%, the gravity segregation of Pb in casting can be removed, and the relationship between solid fraction of alloy mushy and size of Pb particle in ingot is

$$x = -0.58y + 67.1 \qquad (y \geqslant 45)$$

where x is size of Pb particles, y is solid fraction.

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(Edited by YANG Bing)