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Effects of solidification and melt treatment on microstructure and mechanical properties of cast ZA27 alloy ①

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[Abstract] The effects of solidification rate, modifications and pouring temperature on the microstructure and mechanical properties of casting zinc-aluminum alloy ZA27 have been investigated. The results show that the number and distribution of pores are the key factors affecting the mechanical properties of ZA27. A slow solidification rate is beneficial to the ductility, while a rapid solidification rate improves the tensile strength of alloy basically. Among the modification agents RE, Sb-Te, Sb-Te-RE and Sb-Te-Ti-B, the addition of Sb-Te to melt results in the best modified microstructure. The optimum pouring temperature for ZA27 is approximately 550 ℃.

[Key words] zinc-aluminum alloy; porosity; mechanical properties; solidification; microstructure
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1 INTRODUCTION

Zinc-aluminum alloy ZA27 has the best combined properties, especially wear resistance, among zinc based alloys containing a high content of aluminum[1]. Wide ranges of applications have been found for this alloy, and for bearing materials it replaces tin and aluminum bronze. In order to increase its wear resistance, high temperature properties and to prevent its senile change, zinc matrix composites reinforced by SiC_p and Gr_p have been developed[2~4]. Since the alloy has a wide solidification temperature range (109 ℃)[5], it is difficult to cast, and pores always form during casting. The porosity in castings weakens their mechanical properties and limits their application. In order to improve the mechanical properties of cast ZA27 alloy, it is necessary to reduce the lever of porosity in the castings. Since 1980s, many researchers have studied this problem, but the conclusions are different[6~8]. This study is focused on the influences of different solidification conditions, addition of trace elements and pouring temperatures on the microstructure and properties of ZA27 alloy.

2 EXPERIMENTAL PROCEDURE

The composition of ZA27 alloy used in the experiments is: 27% Al, 1% Cu, and 0.03% Mg, with remaining being zinc. Pure Zn, Al, Mg and Al-44% Cu master alloy were used to make the alloy.

Pure Al and Al-44% Cu alloy were melted at 780 ℃ in a graphite crucible by using an electric resistance furnace. Zinc was added at about 700 ℃. When the temperature of the melt decreased to 580 ℃, pieces of magnesium were plunged into the melt. The degassing was done by using 0.2% C_2Cl_6. After slagging-off, the molten alloy was poured into a permanent metal mold, moisture sand mold, dry sand mold and plaster mold respectively. All the casting molds have cylindrical cavity with a size of 13 mm in diameter and 100 mm in depth. The sequence of the above molds with decreasing solidification rate is permanent metal mold, moisture sand mold, dry sand mold and plaster mold.

In order to investigate effects of additives, trace elements, 0.04% RE, 0.04% Sb, 0.04% Sb-0.02% Te, 0.04% RE-0.04% Sb-0.02% Te and 0.04% RE-0.04% Sb-0.02% Te-0.1% Ti-0.028% B (adding in the form of K_2TiF_6 and H_2BO_3 of dehydration) were added to the melt respectively at 590 ℃. After the elements to be added, the melt was held for 30 min at the temperature and then cooled to 550 ℃ for pouring into the permanent mold.

To investigate the effects of melt pouring temperature, different temperatures, 530, 550, 580 and 600 ℃ were also used for the same permanent metal mold preheated to 200 ℃.

3 RESULTS AND DISCUSSION

3.1 Influence of solidification rate on microstructure and properties

Table 1 shows the mechanical properties of unmodificated ZA27 alloy under different solidification conditions with the pouring temperature 550 ℃. It

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can be seen that the alloy cast in the permanent mold shows the highest tensile strength, and the alloy in plaster mold with slow cooling rate shows the second highest tensile strength but the best elongation.

Table 1 Mechanical properties of ZA27 alloy in different solidification condition

Mold	Plaster	Dry sand	Moisture sand	Permanent
σ_b/ MPa	324.5	263.0	275.9	335.2
δ/ %	8.0	1.2	1.0	5.5

It can be observed from the morphology of ZA27 alloy (Fig. 1) that with the increasing of cooling rate (in the order of plaster mold → dry sand mold → moisture mold → permanent mold), the grain size decreases, and the shape and size of pores also change. The samples cast in the plaster and dry sand mold have more and large pores (Fig. 1(a) and (b)). The pores in the samples cast in moisture sand mold are centralized, and their size is about half of the size of the pores in the samples cast in dry sand mold (Fig. 1 (c)). The size of pores in the samples cast in the permanent mold is even smaller (Fig. 1(d)).

The pores in the samples cast in the plaster mold, dry sand mold and permanent mold are well-distributed. With slow cooling (plaster and dry sand mold), the solidification pattern near the mold wall is similar to that close to the center. The condition for the formation of pores is similar to that of the plaster mold and dry sand mold. The only difference is that the pores formed in the samples cast in the plaster mold are large and disconnected, while the pores formed in the samples cast in dry sand mold are elongated and continuous and appear in the inter dendritic regions. For the permanent mold, due to very fast cooling rate, the pores are small and well-distributed. The pores in the samples cast in moisture sand mold are centralized. It is likely that is due to a near planar solidification pattern facilitated by the moisture sand mold.

It is well known that large grains and pores are harmful to the properties of an alloy. But the results of this show that the samples cast in plaster mold with the large grains and large pores have the good properties. Their tensile strength is only inferior to that of the samples cast in permanent mold, while their elongation is higher than that of the samples cast in permanent mold. This anomaly can be explained in the following way. When the samples are cast in a plaster mold, the primary dendrites can grow to a very large size due to small supercooling, and thus the growth of the secondary and tertiary dendrites is suppressed. This is beneficial to feeding of the cavity caused by shrinkage. Because of this, only the large and centralized pores are formed in the samples. Unlike the elongated and continuous pores in the samples cast in dry sand mold, the centralized pores are less harmful to the mechanical properties of the samples because they are less effective in initiating cracks dur-

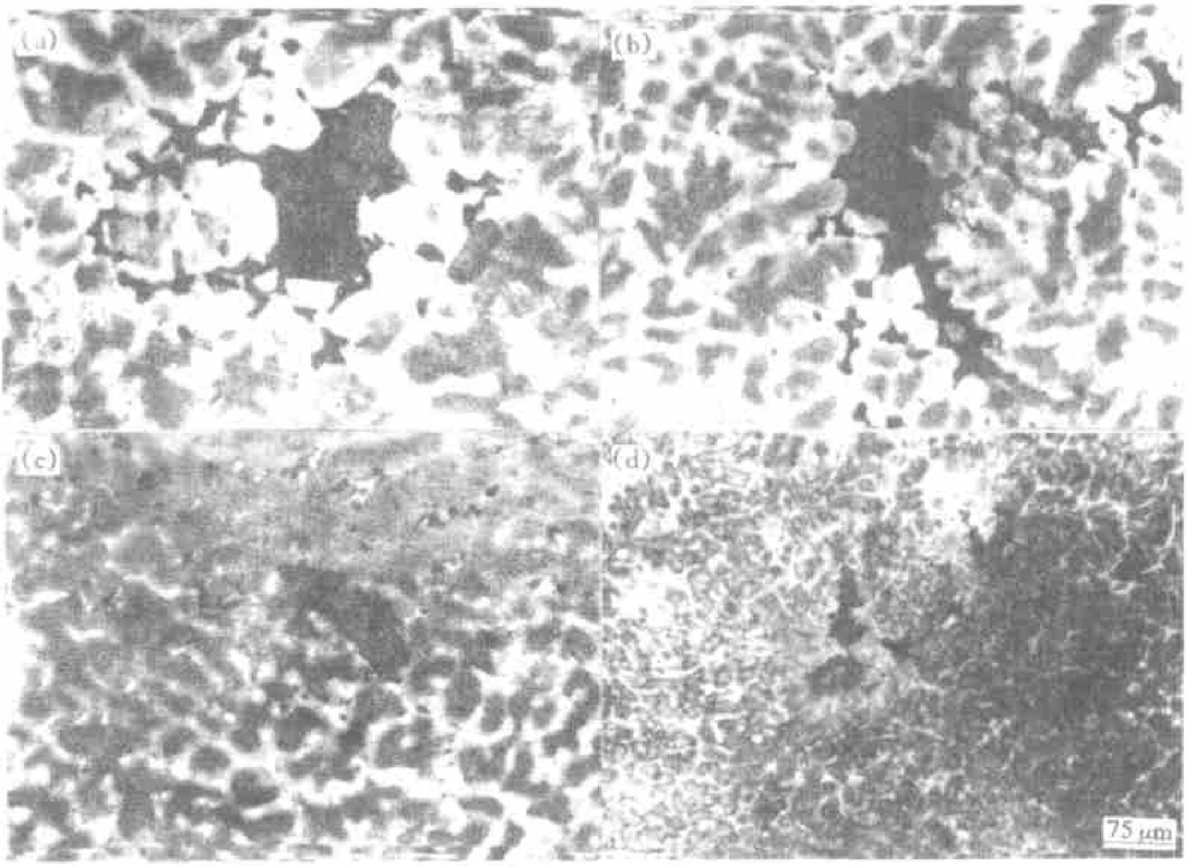

Fig. 1 Size and shape of pores formed under different pouring conditions
(a) —Plaster mold; (b) —Dry sand mold; (c) —Moisture sand mold; (d) —Permanent mold

ing tensile tests.

Under normal conditions, the growth of cracks of ZA27 alloy during deformation occurs along the dendrites rich in zinc and the eutectic zone[7]. That is, the strength of the alloy mainly depends on the properties of the phase rich in zinc and eutectic zones. While in the condition of slow cooling rate (e. g. plaster mold), the dendrites crystal of primary α phase rich in Al and the α′ phase rich in zinc around it will be bulky, and therefore, easy to form pores. The eutectic number is small and the shape is blunt, which will lead to the transgranualar fracture. In this way, the composition of α and α′ in a grain is similar from edge to inter, which leads to good mechanical properties (Table 1). Therefore, the tensile strength and elongation are all higher (Table 1). Under the condition of fast cooling, the number of eutectic zones and the ratio of transgranualar fracture are large. Crystal boundary is the zone rich in bristle phases. With fast cooling, the grain size is small and the specific surface of grain boundary is large, and therefore, the tensile strength is also high.

Fig. 2 shows the fracture surface of ZA27 alloy. The samples cast in plaster mold show ductile deformation except the large pores (Fig. 2(a)). The alloy cast in permanent mold has small pores and a higher density (Fig. 2(b)). The compact part of its microstructure is divided into small zones. The ductile fracture is not obvious. The cross section of alloy solidified in moisture sand mold is the transgranular fracture and shows brittle feature (Fig. 2(c)). The fracture of alloy cast in dry sand mold is along the pores zone and there are a lot of bright spots distributing in the cross section, which are determined by energy spectrum as the phase rich in Fe (Fig. 2 (d)). It should be one of the main reasons.

3.2 Influence of trace elements on microstructure and properties

Table 2 shows the mechanical properties of ZA27 alloy containing different trace elements with the pouring temperature 550 ℃. By comparing the data with those shown in Table 1, it can be seen that the tensile strength of alloy increases after adding the trace elements, but the ductility decreases.

RE can combine with O, N and H in the melt to

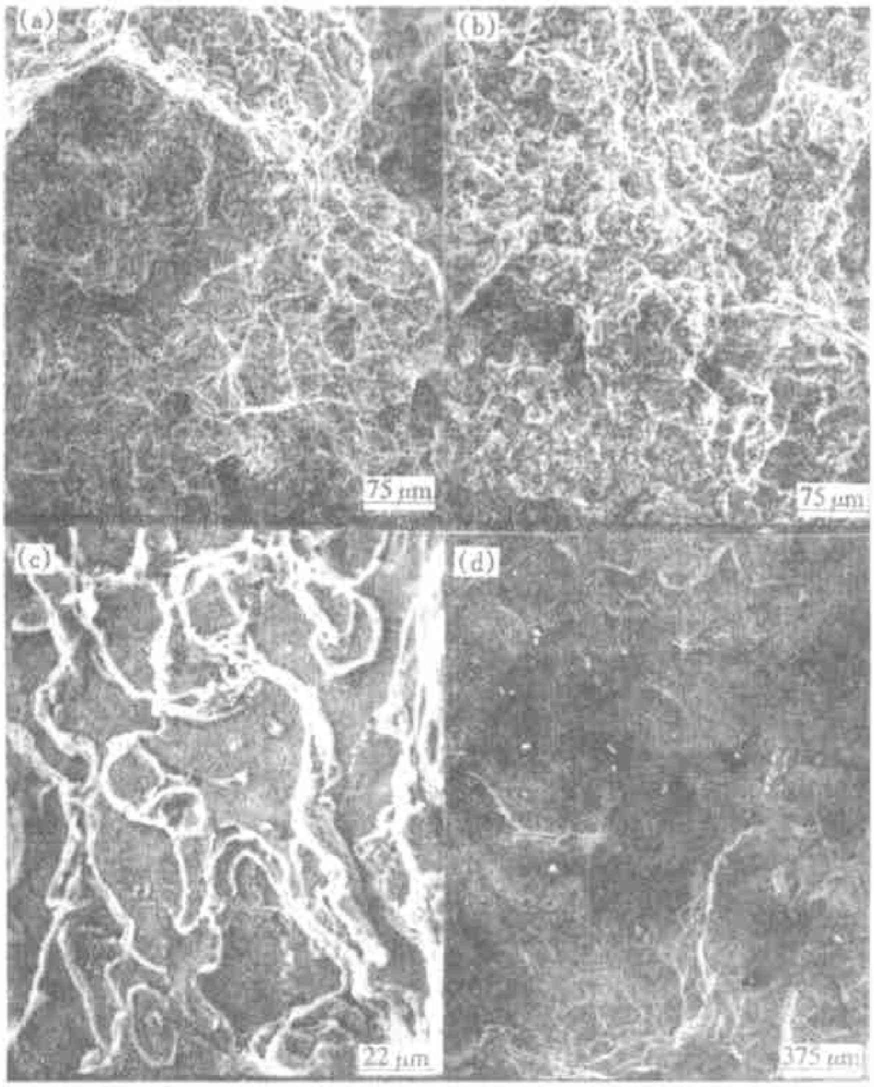

Fig. 2 Fracture morphologies of ZA27 alloy
(a) —Plaster mold; (b) —Permanent mold; (c) —Moisture mold; (d) —Dry sand mold

Table 2 Mechanical properties of ZA27 with trace elements solidified in permanent mold

Elements	RE	Sb	Sb-Te	Sb-Te-RE	Sb-Te-RE-Ti-B
σ_b/MPa	335	371	409	383	381
δ/%	1.5	1.5	2.0	1.3	1.9

form the compounds with low densities and high melting points. These compounds can be easily taken off with slag. In doing so, the gas content in the melt is greatly reduced, and therefore, the tendency of hydrogen embrittlement and the lever of gas porosity in the castings will be decreased. On the other hand, RE can form some compounds such as $LaAl_4$, $CeAl_4$ and Al_4CuCe[8]. Firstly, Al_4Ce and Al_4La can play a role of the heterogeneous nucleants for the zinc rich phases, leading to grains finer and an increased ability for the molten metal to feed the shrinkage cavity. Secondly, RE can prevent the floating of α phase rich in Al, and thus decrease lever of gravity segregation and surface porosity. Finally, RE can combine with Fe in the melt to form the compound (RE, Fe) Al_4Zn_8 and modify the phase rich in Fe[9]. It can be seen from Fig. 3(a) that the microstructure of ZA27 with RE shows no large pores, but a large number of microshrinkage pores distributed along the grain boundary. RE increases the tendency of microshrinkage, which counteracts its other beneficial effects, so the overall effect of RE on the mechanical properties is marginal.

With an addition of antimony, the morphology of grains is similar to that of the alloy with the addition of RE, but the tendency for the formation of pores decreases obviously. The combined addition of antimony and tellurium can make the α phase granular and also decreases the number of large pores. When observed in an optical microscope with a high magnification (Fig. 3(b)), the pores located in grain boundary are not continuous like Fig. 3(a) but disconnected. It can be also seen that there are some grains whose size is lower than 6 μm. The reason is that adding of tellurium can make the other elements to form some compounds as the heterogeneous nucleants of α phases, and thus causes formation of equiaxed grains. For these reasons, the alloy has a much higher tensile strength than that of alloy with RE. The composed addition of Sb-Te-RE can make grains even finer, but it increases the shape and size of the primary phase do not change, but the number of large pores decreases. Some complicate compounds appear in the eutectic structure (Fig. 3(c)), and they are hard and brittle, resulting in worsening of the mechanical properties of alloy.

3.3 Influence of pouring temperature on microstructure and properties

Table 3 illustrates the mechanical properties of ZA27 alloy cast with different pouring temperatures. It can be seen from Table 3 that the ZA27 alloy has the best properties when the pouring temperature is 550 ℃.

Table 3 Mechanical properties of ZA27 alloy under different pouring temperature

Temperature/℃	530	550	580	600
σ_b/MPa	374.5	397.9	381.0	363.2
δ/%	1.4	2.6	1.9	1.5

With the increasing of pouring temperature, the solidification time is prolonged. Since there are so many elements to be added into the melt, some of them are excluded into the eutectic structure and arrears in complicate state for their low solution in α and α′ phase. The phases contains these elements mainly belong to the low melting point bristle compounds. There are a lot of bright phases in the eutec-

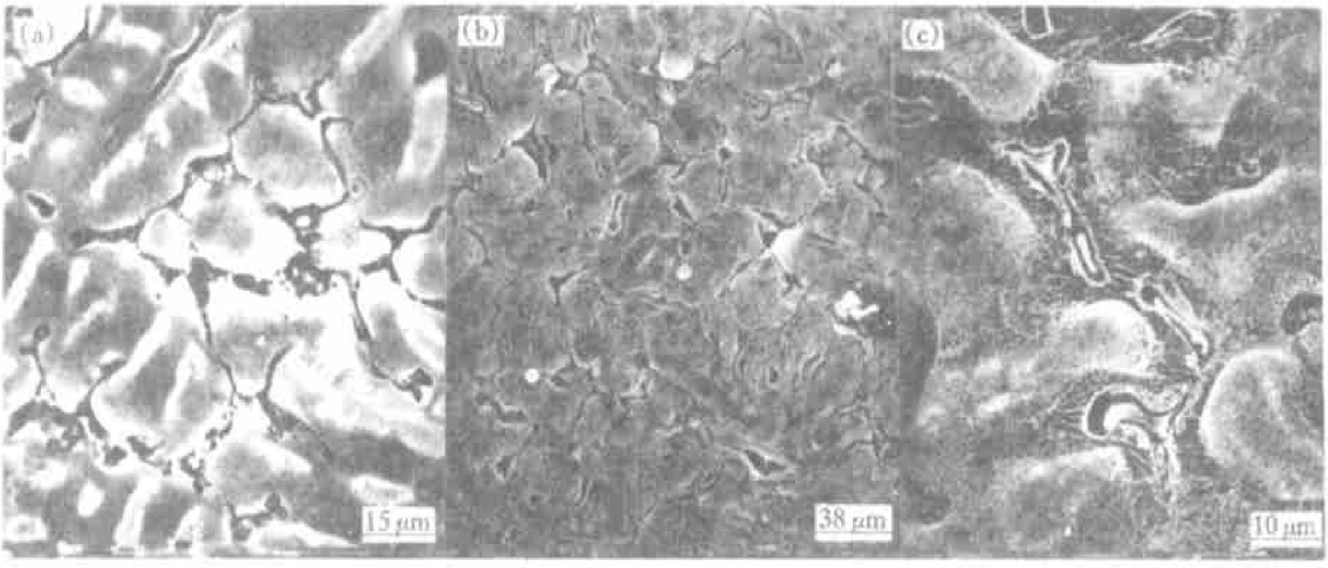

Fig. 3 Morphologies of ZA27 alloy with trace elements
(a) —Microshrinkage at boundary; (b) —Disconnected pores; (c) —Compounds in eutectic structure

tic structure. The alloy poured in 530 ℃ has little amount of this kind of phase, but has a lot of pores; this phase will increase when the alloy is poured in 550 ℃, but it is well-distributed; at 580 ℃, some of these phases appear in the rod or chunk shape; when pouring temperature is 600 ℃, these phases seem to have the continuous web structure. Based on Table 3, it can be concluded that this is a kind of brittle phase and harmful to the mechanical properties.

Although there is a little brittle phase when pouring at the low temperature, the viscosity of alloy is high. It is unfavorable for feeding and easy to form intergranular shrinkage[10], and therefore, decreases the combined strength of grain boundaries, as shown in Fig. 4.

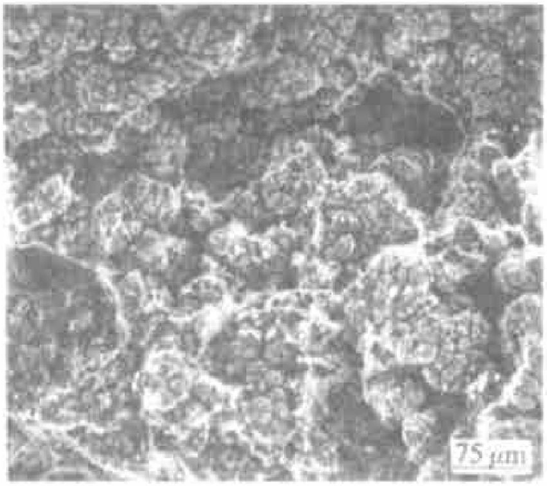

Fig. 4 Fracture of ZA27 alloy poured at 530 ℃

4 CONCLUSIONS

1) Pores are the controlling factors which influence the mechanical properties of ZA27 alloy. Fast cooling in permanent mold can make the pores small and well-distributed, and therefore, increase the tensile strength of ZA alloy. Although ZA27 alloy cast in moisture sand mold solidifies in the form of skin-solidification, it forms long pores zone along the axial line, and thus the strength decreases.

2) A combined addition of antimony and tellurium has a good effect on the microstructure, making grains finer and more equiaxed, but it increases the tendency for the formation of pores.

3) The optimum pouring temperature is 550 ℃. A lower pouring temperature make it difficult to feed shrinkage cavities and thus increases the number to pores, while a higher pouring temperature make it easy for the bristle phases to form and to be distributed along grain boundary.

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