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Strengthening technology and mechanism for semi-solid die casting of aluminum alloy①

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Abstract: Combined with theoretical evaluation, an optimized strengthening process for the semi-solid die castings of A356 aluminum alloy was obtained by studying the mechanical properties of castings solution treated and aged under different conditions in detail, then, the semi-solid die castings and liquid die castings were heat treated with the optimized process. The results show that the mechanical properties of semi-solid die castings of aluminum alloy are superior to those of the liquid die castings, especially the strengthening degree of heat treated semi-solid die castings is much greater than that of liquid die castings with the tensile strength more than 330 MPa and the elongation more than 10%, and this is mainly contributed to the non-dendritic and more compact microstructure of semi-solid die castings. The strengthening mechanism of heat treatment for the semi-solid die castings of A356 aluminum alloy is due to the dispersive precipitation of the second phase(Mg_2Si) and formation of GP Zone.

Key words: aluminum alloy; semi-solid die casting; strengthening of heat treatment; microstructure
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1 INTRODUCTION

Semi-solid metal forming (SSM or SSF) has extensively applications in many industries, especially in the automobile industry since it was discovered in the 1970s[1-6]. This is because it has superiority over the conventional liquid forming (die casting) with it's more compact microstructure, less entrapment of gas and higher mechanical properties, as well as it has superiority over the solid forming (forging) in energy saving, longer life of mould and net shape formingability.

Aluminum alloys have a series of advantages, such as superior formability and better mechanical property, higher specific strength etc, so they are one of the most suitable alloys for semi-solid forming and for the reduction of vehicle mass. However, there is few research works concerning the strengthening mechanism on heat treatment of semi-solid forming aluminum alloys and there exist many problems in this field[7-9], such as how is the relationship between strengthening and hardening in semi-solid or liquid die castings of A356 aluminum alloy? Although, there are some papers presented on the technique and theory of heat treatment for the semi-solid forming of aluminum alloy[10-14].

The main purpose of this paper is to study the effect of solution treatment and ageing on the microstructure and properties of semi-solid die casting of A356 aluminum alloy, meanwhile the strengthening mechanism of semi-solid die castings are discussed in detail by comparing it with that of liquid die castings from the point of view of microstructure.

2 EXPERIMENTAL

The materials used in the experiment are A356 aluminum alloy billets with non-dendritic microstructure which are prepared by electromagnetic stirring. The composition of A356 aluminum alloy is listed in Table1.

Table1 Chemical composition of A356 aluminum alloy (mass fraction, %)

Si	Mg	Zn	Cu	Mn	Fe	Ti	Al
6.83	0.35	0.17	0.003 6	0.003 5	0.1	< 0.001	Bal.

The billets are machined into a defined size of round bars according to the mass of the part to be formed, then inductively heated to semi-solid and die cast with 500 t horizontal and cold chamber die casting machine.

In order to ensure the homogeneity and precision of heated temperature, all the die castings are solution treated in the nitrate bath and then aged in the oven with fan in different conditions.

The hardness and mechanical properties of heat treated semi-solid die castings or liquid die castings are measured with hardness tester and mechanical testing and simulation (MTS), respectively. Meanwhile the optical microscope and transmission electron

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microscope are used to analyze the evolution of microstructure and precipitation of strengthening phase in the die castings.

3 RESULTS AND DISCUSSION

3.1 Effect of solution temperature on properties of semi-solid die castings

The mechanical properties of semi-solid die castings of A356 alloy varied with solution temperature as shown in Fig. 1.

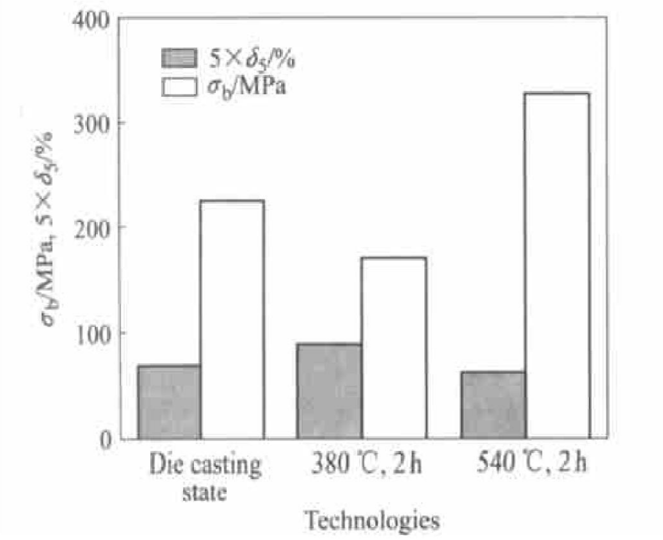

Fig. 1 Effect of solution temperature on properties of semi-solid die castings of A356 alloy after aged at 170 ℃ for 8 h

It can be seen from Fig. 1 that the mechanical properties of semi-solid die castings vary noticeably with the solution temperature. In engineering application, however, higher tensile strength is often needed, so the 540 ℃ is chosen as the solution temperature for semi-solid die castings. The lowest strength and the highest elongation of semi-solid die castings of A356 aluminum alloy solution treated at 380 ℃ and aged at 170 ℃ is due to the dissolution of GP Zone formed during air cooling of die castings and the little ageing effect during such heat treatment process[15].

3.2 Effect of solution time on properties of semi-solid die castings

The semi-solid die castings of A356 aluminum alloy are solution treated with different soaking time at 540 ℃, then its hardness was measured immediately and the results are listed in Table 2. Typical microstructure of solution treated die castings are shown in Fig. 2.

It can be seen obviously from Table 2 that the hardness of the semi-solid die castings of A356 aluminum alloy increases with the solution treatment time before 2 h at 540 ℃, then decreases with increasing solution treatment time. Because there are two contrary effects, that is, strengthening of solution treatment and softening of grain coarsening (Fig. 2) during soaking of solution treatment, solution treating at 540 ℃ for 2 h is chosen as a reasonable process.

The alloying element silicon diffused into the

Table 2 Effect of solution heat treatment time on hardness of semi-solid die castings of A356 aluminum alloy

Solution treatment time/h	Brinell hardness
0	63.1
1	64.9
2	65.4
4	61.7
6	59.8
8	54.5

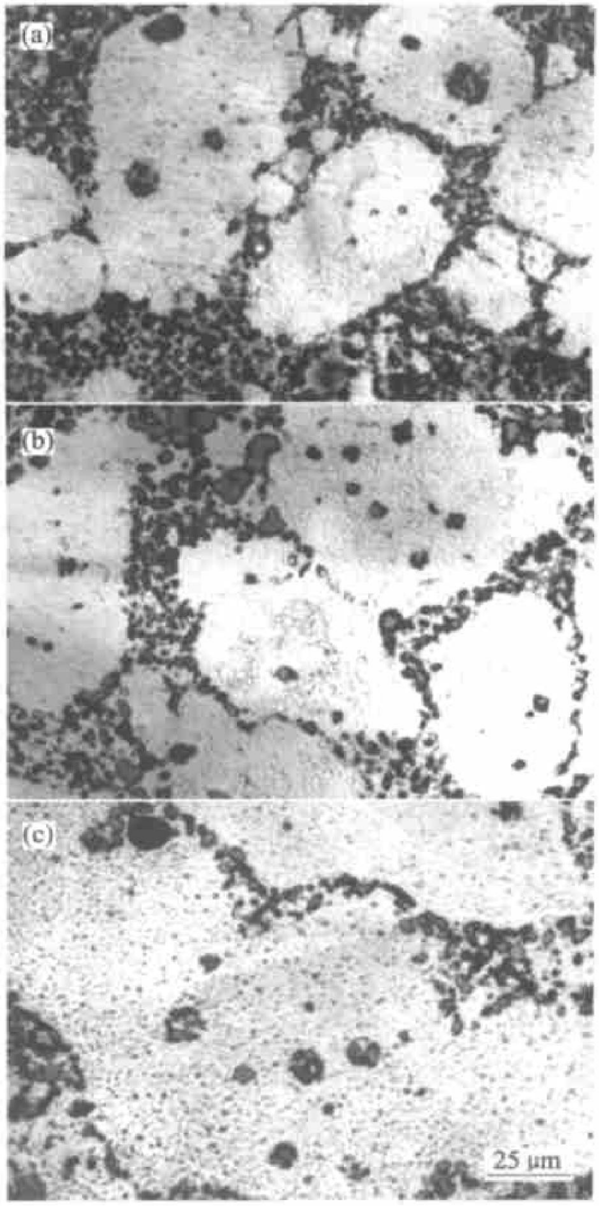

Fig. 2 Typical microstructure of semi-solid die castings of A356 aluminum alloy solution treated at 540 ℃ under different soaking time
(a) —1 h; (b) —2 h; (c) —8 h

primary α(Al) phase with sphere particle during solution treatment was considered, and the diffusion sketch is shown in Fig. 3. In Fig. 3 o is the origin of diffusion distance (r) axis located at grain boundary.

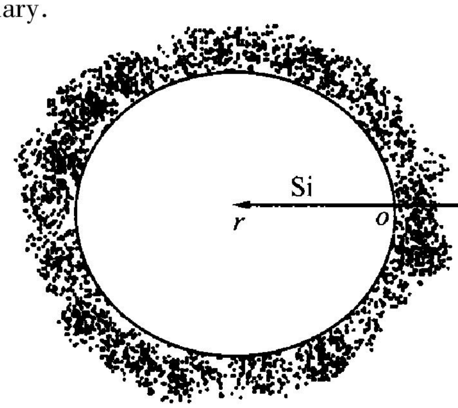

Fig. 3 Sketch of silicon diffusing into primary α-Al particle with average radius R_o(R_o= 120 μm)

According to the second Fick's diffusion law, the following formula can be deduced for one dimension:

$$\frac{\partial c(r, t)}{\partial t} = D \frac{\partial^2 c(r, t)}{\partial r^2} \quad (1)$$

where $c(r, t)$ is the content of silicon at r position in the time t, D is diffusion coefficient, t is diffusion time, r is diffusion distance.

According to the Al-Si phase diagram, the content of silicon in eutectic point is 12.5% (mass fraction), and the saturation of solution silicon in the α-(Al) phase at 540 ℃ is about 1.3% (mass fraction). So we can make following suppositions for A356 aluminum alloy.

Boundary condition:

$$c(r=0, t) = c_S = 12.5\% \quad (2)$$

Initial condition:

$$C(2R_0 > r > 0, t = 0) = 0 \quad (3)$$

On the basis of Eqns. (2) and (3), the solution of the Eqn. (1) is as follows:

$$c(r, t) = c_S\left(1 - \mathrm{erf}\left(\frac{r}{2\sqrt{Dt}}\right)\right) \quad (4)$$

where c_S is the mass fraction of Si atom at the grain boundary.

If the content of Si in the center of the α-Al particle reaches to 1.3% at 540 ℃ by diffusion, the time t is taken as t_0, which can roughly represent the soaking time during the solution treatment.

Substituting the relative parameter into Eqn. (4), it can be obtained:

$$t_0 = \left(\frac{0.012}{2.304}\right)^2 / D \quad (5)$$

Substituting $D_{540\ ℃} = 3.89 \times 10^{-9}\ \mathrm{cm^2/s}$[16] into Eqn. (5), then

$$t_0 = 1.94\ \mathrm{h}$$

It can be found that the estimated diffusion time t_0= 1.94 h is very close to the experimented result (2 h), and this, in the other hand, indicates the chosen soaking time of 2 h at 540 ℃ solution treatment is reasonable.

3.3 Effect of ageing on properties of semi-solid die castings

The semi-solid die castings of A356 aluminum alloy were firstly soaked for 2 h at 540 ℃ and aged at different temperatures with varying time, then the hardness of aged specimen was measured. The corresponding ageing curves are displayed in Fig. 4. The ageing curve of liquid die castings of A356 aluminum alloy is also displayed in Fig. 4.

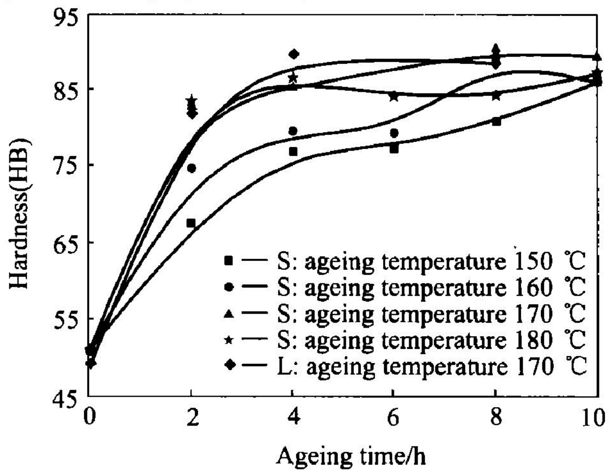

Fig. 4 Effect of ageing technologies on hardness of semi-solid die castings and liquid die castings of aluminum alloy
(L —Liquid die casting; S —Semi-solid die casting)

From Fig. 4, it can be found that the hardness of aged semi-solid die castings of A356 aluminum alloy increases with ageing time before 10 h when the temperature is below 170 ℃; while ageing at 180 ℃, there is an ageing peak at about 4 h, so the ageing technology of 170 ℃, 8 h is chosen in the latter heat treatment. It can also be seen that the liquid die casting of A356 aluminum alloy has similar ageing trend, which indicates that the hardening degree of liquid die castings is the same as the semi-solid die castings during ageing process.

3.4 Effect of heat treatment on properties of semi-solid and liquid die castings

The semi-solid and liquid die castings of A356 aluminum alloy are solution treated and aged at the process of 540 ℃, 2 h soaking and water quenching, then 170 ℃, 8 h ageing. The measured mechanical properties of the die castings are listed in Table 3. The typical morphologies of optical and transmission electron microscope (TEM) are shown in Figs. 5 and 6, respectively.

It is clearly from Table 3 that the properties of semi-solid die castings of A356 aluminum alloy is superior to those of the liquid die castings either in

Table 3 Comparison of mechanical properties of semi-solid die castings and liquid die castings of aluminum alloy heat treated in same condition

State	σ_b/MPa	δ_5/%
Liquid castings	216.2	8.7
Heat treated liquid castings	276.9	3.4
Semi-solid castings	220.8	16.8
Heat treated semi-solid castings	327.9	12.7

Technology of heat treatment: 540 ℃, 2 h of solution treatment + 170 ℃, 8 h ageing

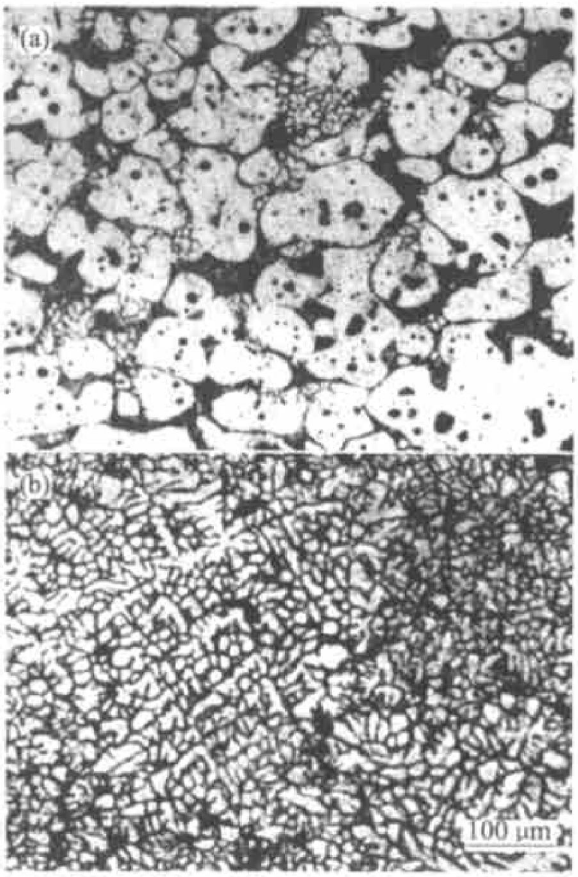

Fig. 5 Typical microstructure of semi-solid and liquid die castings of aluminum alloy
(a) —Semi-solid die castings; (b) —Liquid die castings

die casting state or in heat treated state. Because the microstructure of semi-solid die castings is non-dendrite and more compact than that of the liquid die castings(Fig. 5), it will further deduce that the semi-solid forming of metals possesses more potential of applications.

It can be obtained by comparing the ageing curves of semi-solid casting with those of liquid die castings that both the two die castings have similar varying trend during ageing, so it could be inferred that both the die castings possess age hardening effect. The mechanism of hardening of the semi-solid die castings is the dispersive precipitation of the second phase(Mg_2Si) and formation of GP Zone during ageing[15], and it can be seen in the TEM morphologies(Fig. 6).

On the other hand, only the semi-solid die castings of A356 aluminum alloy have age strengthening, while the liquid die castings has little age strengthening by analyzing the results in Table 3, although they have the similar age hardening effect. The microstructure of semi-solid die castings is non-dendrite, while the liquid die castings are dendrite, which can be observed from Fig. 5. It is known that the dendritic microstructure will cause concentration stress when applying tensile load, which results in the decrease of strength of liquid die castings even if the castings possesses same level of hardness as that of semi-solid die castings.

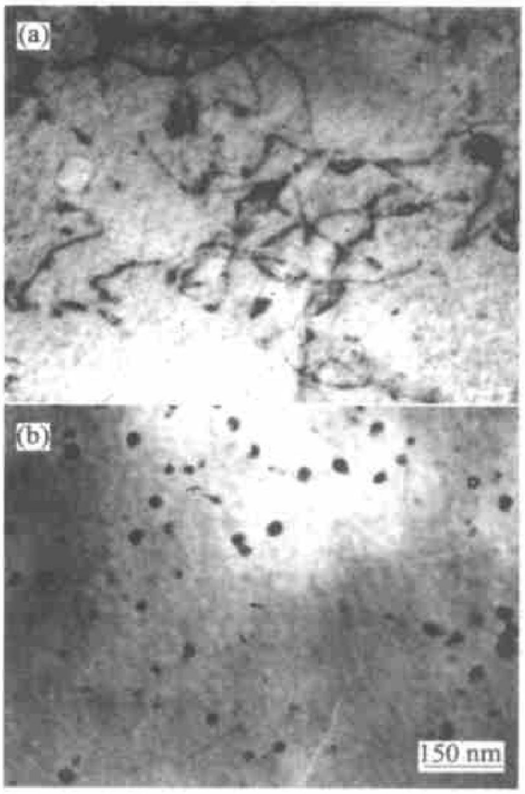

Fig. 6 Typical TEM of semi-solid die castings of A356 aluminum alloy
(a) —Die casting state; (b) —T6 state

4 CONCLUSIONS

1) The ductility and strength of semi-solid die castings of A356 aluminum alloy are superior to those of liquid die castings. This is mainly contributed to the non-dendritic and compact microstructure in the semi-solid die castings.

2) Both the liquid die casting and semi-solid die casting of A356 aluminum alloy possess age hardening effect, but only the semi-solid die castings has age strengthening effect. The optimum strengthening process of semi-solid die castings of A356 aluminum alloy is 540 ℃, 2 h+ 170 ℃, 8 h.

3) The mechanism of age hardening and

strengthening is mainly contributed to the dispersive precipitation of the second phase(Mg_2Si) and formation of GP Zone.

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