THE EFFECT OF SOLIDIFICATION RATE ON THE FATIGUE PROPERTIES OF THE ALUMINUM ALLOY CASTINGS

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ABSTRACT For fabricating the complex shape castings, plaster mold casting is used. To improve mechanical properties of plaster mold castings, the effect of cooling rate on tensile property and fatigue property are studied with 354 alloy and Al-5%Cu-0.4%Mg-0.2%Si alloy using DAS measurement method. It is found that tensile strength and elongation of 354 alloy castings increase as DAS decreases and 0.2% proof stress is not sensitive to DAS, and fatigue property increases with a decrease in DAS. Tensile property of CMS alloy castings is improved as DAS decreases, and fatigue property is not sensitive to DAS. DAS measurement is a suitable method to understand effect of cooling rate on mechanical property of 354 alloy and CMS alloy castings.

Keyword: *cooling rate, Dendrite-Arm-Spacing, fatigue property, 354 alloy*

1. INTRODUCTION

The plaster mold casting and/or sand mold castings are important processes to fabricate complex shape castings. It is well known that castings fabricated by these processes have lower mechanical properties because of low solidification rate. Recently, higher mechanical properties are desired even in complex shape castings. From this standpoint, the authors are studying about improvement of mechanical properties of plaster mold castings. The objective of this study is to make the effect of the solidification rate on mechanical properties, especially fatigue property, clear in aluminum plaster mold castings.

2. EXPERIMENTAL PROCEDURES

2.1 Preparation of specimens

The ASTM 354 alloy and Al-5%Cu-0.4%Mg-0.2%Si alloy (mass %, written as CMS alloy in this study) were used in this work. The chemical compositions of these alloys are shown in Table 1. CMS alloy has a composition correspond to A206 or A201 alloy and has higher fatigue property than 354 alloy.

Table 1 Chemical composition of 354 alloy and CMS alloy (mass %)

alloy	Cu	Si	Mg	Fe	Mn	Ti	Bi	Al
ASTM_354	1.80	9.00	0.55					Bal.
CMS	4.90	0.30	0.30	0.10	0.21	0.17	-	Bal.

Melts are prepared in a carbon crucible using an electric resistance furnace. The schematic drawing of vacuum furnace is shown in Figure 1. In 354 alloy, 0.05wt% Sr was added to the melt by commercial Al-90wt%Sr master alloy for modification and 0.2wt% Ti was added to the melt by Al-5%Ti-1%B master alloy for grain refinement. In CMS alloy, only 0.2wt% Ti was added to the melt. The degasification of 354 and CMS melt was performed in vacuum for 40 minutes. In 354 melt, stirring was done with vacuum degasification and in CMS melt, stirring was not performed. Temperature of melts was stabilized at about 983 K in both melts.

To study the effect of cooling rate on mechanical properties, three types of castings were used in this work. One is rectangular bar cast into permanent mold, another is impeller cast into plaster mold and the other is cylinder cast into plaster mold. The bar has 20 mm width, 40 mm height, and 180 mm length. The impeller has about 90 mm diameter and 90 mm height. The cylinder has 80 mm diameter and 150 mm height. The gravity casting was used in this work. The plaster molds are preheated at 423 K and permanent mold was not preheated. The casings were unidirectionally solidified using chill plate that is sprayed with jet of cooling water when the temperature is above 373 K. The pour temperature was about 983 K in 354 alloy and about 1008 K in CMS alloy.

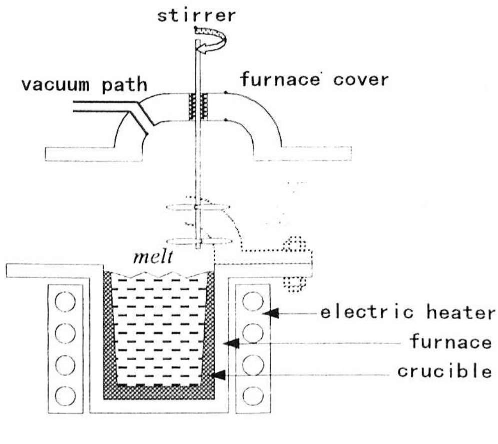


Fig. 1 Schematic drawing of vacuum furnace.

HIP (Hot Isostatic Pressing) treatment was performed to all castings in order to reject the influence of casting defects on mechanical properties. HIP condition is 1 hour keep at 778 K and 10.1MPa. T6 heat treatment was performed after HIP treatment. T6 conditions are as follows; solution treated for 9 hours in 800 K and aging treated in 450 K for 4 hours in 354 alloy and solution treated 793 K for 14 h and aging treated in 473 K for 5 hours in CMS alloy.

2.2 Quantify the cooling rate

The cooling rate was monitored by three thermocouples placed at various intervals along the length of the mold. The cooling rate was measured in impeller and cylinder. The locations of thermocouples are 30, 60 and 90mm above the chill plate in cylinder castings, and 10 and 40mm above the chill plate in impeller castings. The cooling rate at each location was defined as the average cooling rate between 884 and 826 K in 354 alloy and between 915 and 848 K in CMS alloy (i.e. the liquidus and solidus temperatures of 354 alloy and CMS alloy).

The effect of cooling rate on mechanical properties of castings was studied using Dendrite Arm Spacing measurement method (DAS method) [1]. DAS was measured in five optical microphotographs of 100 magnifications using cross-line method. The average of five values was defined as DAS at that region. The measurement was done in only polished specimens in 354 alloy castings but was done in etched specimens in CMS alloy casting. The floating crystals were excluded.

2.3 Evaluation of mechanical properties

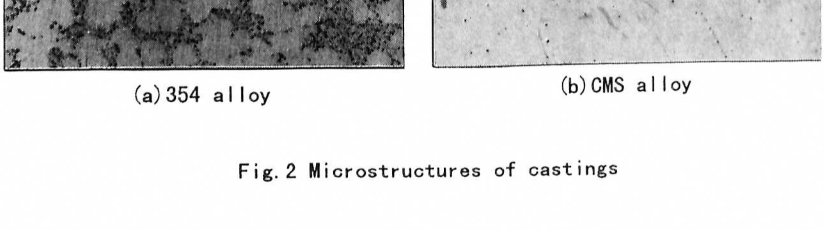
The mechanical properties ware evaluated with tensile test and rotating beam fatigue test. Tensile strength was measured with all types of castings and fatigue property was measured with rectangular bar shape castings and cylinder castings. Tensile and fatigue tests were done in room temperature.

3. RESULTS AND DISCUSSION

3.1 The relationships between the cooling rate and DAS

Microstructures of castings are shown in Figure 2. The microstructures of 354 alloys castings showed dendritic microstructure, but that of CMS alloy castings hardly showed dendritic structures. There are no defects larger than 50 μm in all castings after HIP treatment. Therefore, it can be concluded that effect of defects on mechanical properties of castings is negligible in this study.

The Figure 3 shows the cooling rate in each position of castings. The horizontal axis shows a distance from chill plate. In cylinder castings, the cooling rate is 0.22 K/s in the position that is 30mm above the chill plate and is 0.05 K/s in the position that is 90 mm above the chill plate. In both impeller castings and cylinder castings, the cooling rate decreased as the distance from chill plate increased. However, DAS of cylinder casting is bigger than that of impeller casting at the same distance position from chill plate. This is caused by the differences of heat capacity in both shapes of castings.



(a) 354 alloy (b) CMS alloy

Fig. 2 Microstructures of castings

Relationship between DAS and cooling rate of 354 alloy castings is shown in Figure 4. DAS of bar castings fabricated by permanent mold is about 70 μm, so it is predicted that the cooling rate of this shape of casting is about 0.8 K/sec. This cooling rate is similar to the value that measured in impeller castings by plaster mold. The relationship between DAS and cooing rate showed that DAS is proportional to about one-third power of cooling rate that agrees with the general relationship [1]. In this work, DAS of impeller is similar to that of bar castings. This suggested that controlling the cooling rate of impeller castings could improve mechanical properties of complex shape castings.

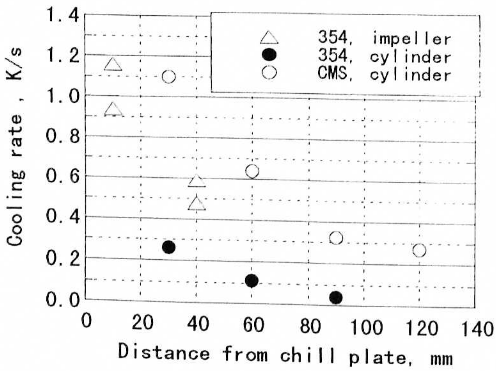


Fig. 3 Relationships between cooling rate and distance from chill plate.

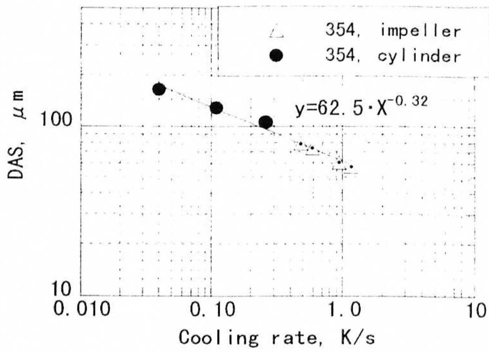


Fig. 4 Relationship between cooling rate and DAS for 354 alloy castings.

3.2 The relationships between DAS and tensile properties

The relationships between DAS and tensile strength, 0.2 % proof stress and elongation are shown in Figure 5. Tensile strength and elongation increased as DAS decreased, however, 0.2 % proof stress is not sensitive to DAS in 354 alloy castings. In CMS alloy castings, tensile strength and 0.2 % proof stress increased as DAS decreased. The change of mechanical properties are remarkable in the range that DAS is smaller than 100 μm in both alloy castings. Fracture was occurred at eutectic silicon region in 354 alloy castings and was occurred along grain boundary in CMS alloy castings.

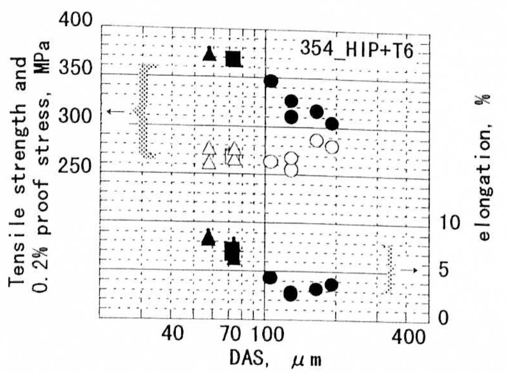


Fig. 5(a) Relationships between tensile properties and DAS.
□, ■:bar, △, ▲: impeller, ○, ●:cylinder

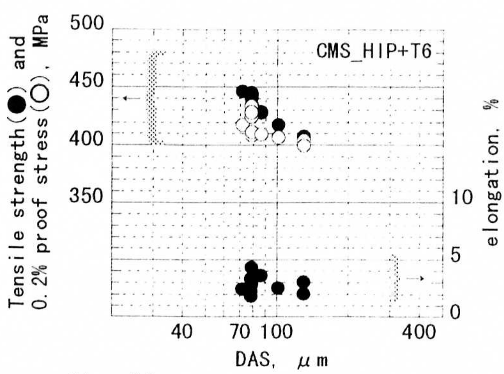


Fig. 5(b) Relationship between tensile properties and DAS.
○, ●:cylinder

3.3 The relationships between DAS and fatigue properties

The relationships between DAS and fatigue properties are shown in Figure 6. In 354 alloy castings, specimens with three different DAS values were prepared; 190, 112 and 72 μm castings. Fatigue property was improved with decreases of DAS; 190 μm DAS castings showed lowest strength and 72 μm DAS castings showed higher strength. 72 μm DAS castings seem to have higher property in potential but have wide scatter in test results. When the property of 72 μm DAS castings is estimated in lowest value, the properties of both castings that 72 μm DAS and 112 μm DAS are in almost equal. The SEM photographs of the fracture surface of bar castings are shown in Figure 7. In all bar castings, obvious defects that may cause fracture are not observed in fracture surface and large defects which sizes more than 50 μm don't exist in the section near the fracture surface. The effect of decrease in DAS on mechanical property improvement is generally depending on the defects dispersion and decrease of defects diameters. However, the size of defects of this work is almost equal in all specimens with variable DAS value because of HIP treatment. Therefore, the improvement of fatigue property is caused by decrease of DAS. The reason why test results were scattered in 72 μm castings is came from the increase of area ratio of defects. The cross section of fracture surface is shown in Figure 8(a). 354 alloy has primary aluminum dendrites and eutectic silicon phase and the each size of eutectic region decreased as DAS decreased. Fractures were usually occurred in eutectic regions, and defects are formed in eutectic region, too. This means that the area ratio of defects against eutectic region area increased with decrease of DAS. Therefore, the sensibility of fatigue property against the same size of defects is increased in smaller DAS castings.

In CMS alloy castings, specimens with two different DAS values were prepared; 130 μm and 78 μm castings. It was appeared that fatigue strength of CMS alloy castings is higher than that of 354 alloy castings. However, DAS hardly effect on fatigue property. Some drop of fatigue life is observed in only higher stress region. The SEM photograph of fracture surface and the cross section are shown in Figure 7(b) and Figure 8(b). In 78 μm DAS castings, the scatters of test results that is observed in 354 alloy castings are not found. Size of defects in CMS alloy castings is similar with that in 354 alloy castings, so the small scatter proved that defects of this size hardly affect the fatigue property in CMS alloy castings.

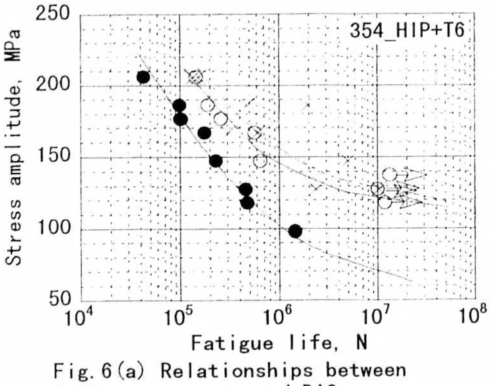


Fig. 6 (a) Relationships between fatigue property and DAS.
DAS = 72 μm; ×, 112 μm; ○, 190 μm; ●

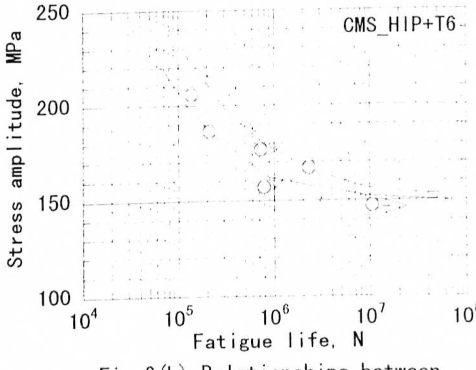
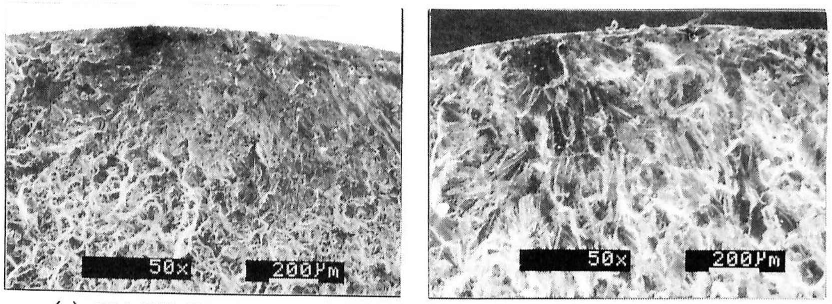
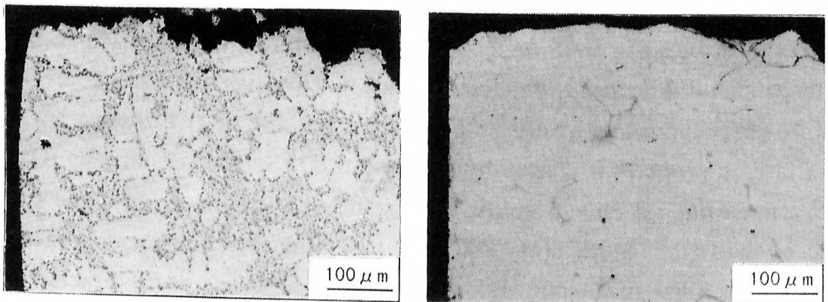


Fig. 6 (b) Relationships between fatigue property and DAS.
DAS = 78 μm; ×, 130 μm; ○



(a) 354_HIP+T6, bar casting (b) CMS_HIP+T6, bar casting

Fig. 7 SEM photographs of the fracture surface



(a) 354_HIP+T6, bar casting (b) CMS_HIP+T6, bar casting

Fig. 8 Microstructures of the cross section of fracture surface

4.CONCLUSIONS

1. It is appeared that DAS measurement is suitable method to understand effect of cooling rate on mechanical property of 354 alloy and CMS alloy castings.

2. Effect of cooling rate on tensile property and fatigue property of 354 alloy and CMS alloy castings are found. In 354 alloy, tensile strength and elongation increase as DAS decreases and 0.2% proof stress is not sensitive to DAS, and fatigue property also increases with a decrease in DAS. Tensile property of CMS alloy castings is improved as DAS decreases, and fatigue property is not so sensitive to DAS.

3. Higher cooling rate (smaller DAS) improves the mechanical properties, but it also increases the sensibility of fatigue property against defects in 354 alloy castings.

REFERENCE

[1] Committee of casting and solidification: J. Jpn. Inst. Light Metals, Light Metals, 38(1988), 54