FATIGUE BEHAVIOR IN Al-Si-Cu DIE CAST ALLOYS

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ABSTRACT The effects of silicon and aging treatment on microstructure and fatigue behavior in three die cast aluminum-silicon alloys are demonstrated. The increase of silicon content drastically changes the morphology of primary silicon particles. The influence of these microstructure changes on fatigue behavior is evaluated by fatigue strength and fatigue crack growth rate tests. Material containing casting defect shows a significant reduction in fatigue life. Cracks are easily initiated from casting defects and most of the fatigue life is spent in fatigue crack growth region. The fractographic study of fractured specimens after fatigue tests reveals the fracture surfaces consist of the cleavage fracture of Si and intermetallic compound particles, and the striation pattern of aluminum matrix.

Keywords: *Die cast alloys, fatigue crack growth rate, casting defect, primary Si, microstructure*

1. INTRODUCTION

Hypereutectic Al-Si cast alloy having low coefficient of thermal expansion, excellent heat-resistance and wear property, is often used as a piston material of automobile engine. However, castability and mechanical property of this alloy are remarkably inferior because primary Si particles are crystallized in coarse and irregular state. The shape, size and distribution of the primary Si particles is well known to depend on the presence of impurities in the metal, the cooling rate during solidification, and the use of refining agents(such as phosphorous)[1,2,3]. In this study, addition of phosphorus (P) as refining agent and subsequently die cast process is applied. However, few reports have been published on the fatigue behavior of hypereutectic Al-Si die cast alloys[4]. In the study, therefore, fatigue life and fatigue crack propagation characteristics are evaluated in several Al-Si-Cu die cast alloys.

2. EXPERIMENTAL

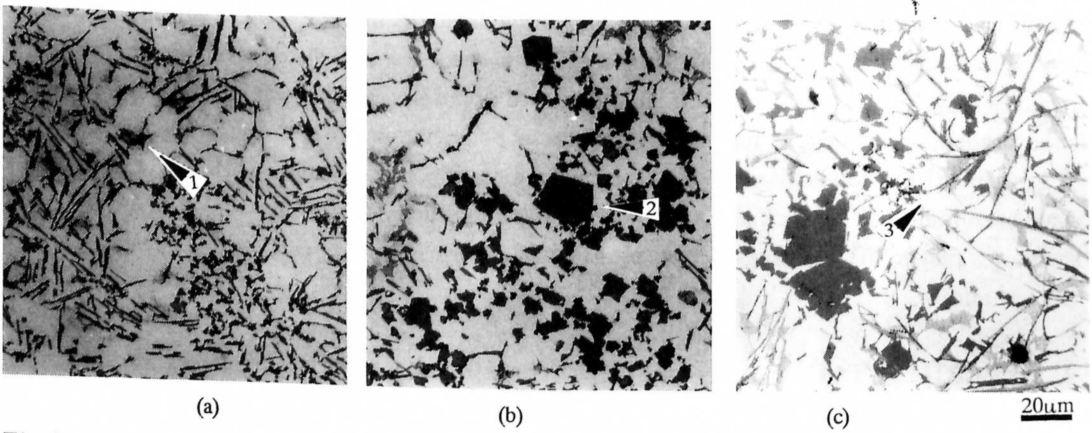
Commercial alloys: ADC12 and the B390, and a newly developed Al-15%Si alloy were used as experimental materials. The Al-15%Si alloy is chosen due to its smaller primary Si particles. The chemical compositions of the alloys are shown in Table 1. The alloys were cast using a PF die casting machine(TOSHIBA 350t DCM type) which has plunger speed of 1.8m/s and casting pressure of 850kgf/cm^2, and a permanent mold of 150×180×11mm was used. Both as cast and T5 heat-treated alloys were prepared. Fatigue tests were performed according to the ASTM E466 standards using cylinder specimens. After machine, the specimens were mechanically polished to a fine finish(0.3μm). An electric servo hydraulic fatigue testing machine was used with a sine wave tension-to-tension load under stress control at ambient temperature. A stress ratio, R, was 0.1. A frequency, f, was 50Hz. Fatigue crack propagation tests were performed using the same fatigue testing machine. Compact tension(CT) specimens with thickness(B) of 8mm and width(W) of 50mm were used. Constant load amplitude test was performed to obtain fatigue crack growth rate curves according to ASTM E 647. Crack length was measured on polished specimen surfaces using a low power(25) traveling microscope. Fatigue crack growth rates were determined by means of the secant method. For the investigation of crack closure behavior, the back face strain measurement is used. Following fatigue test, fracture surfaces of the specimens were carefully examined and areas of cast defect(mainly shrinkage pore) were measured using image analysis.

Table 1 Chemical compositions. (mass%)

	Si	Fe	Cu	Mg	Mn	Cr	P
ADC12	11.2	0.74	2.58	0.26	0.22	—	0.0018
Al-15%Si	14.4	0.87	2.84	0.71	0.49	0.20	0.0048
B390	16.6	0.92	4.32	0.55	0.05	—	0.0045

3. RESULTS AND DISCUSSION

Figure 1 shows optical microstructures of three alloys investigated. The microstructures are typical of die cast Al-Si-Cu alloys. The major phase is primary silicon particles with interdendritic networks of Al-Si eutectic. Al_2Cu is presented as block-like and eutectic-like particles in the interdendric regions. Fe-Mn-Cr-Al and needle-like β-Al_5FeSi particles are also presented in Al-15%Si and B390 alloys, respectively.



(a) (b) (c)

Fig.1. As cast microstructures of die cast Al-Si alloys. (a) ADC12 (b) Al-15%Si (c) B390 alloy. Arrows 1, 2 and 3 show Al_2Cu, Fe-Mn-Cr-Al and β-Al_5FeSi particles, respectively.

The fractographic investigation after fatigue test revealed that the fatigue cracks almost always initiated from shrinkage pores at or close to the specimen surface, which is also in accordance with findings by Couper et al.[5]. The areas of these casting defects on fracture surface are shown in Fig. 2. It is considered that the sizes of the casting defects are dependent on the sampling site and die cast process, but not dependent on silicon content. The areas of casting defects in ADC12-F, Al-15%Si-T5 and B390-F die cast alloys or in ADC12-T5, Al-15%Si-F and B390-T5 die cast alloys are almost the same level. The S-N_f curves for different die cast alloys are shown in Fig. 3 and Fig. 4. The figures clearly show the reduction in fatigue life due to the increase of silicon content and the areas of casting defects, i.e. the casting defects reduced the crack initiation life, and most of the fatigue life is spent in the growth of cracks. The figures also show remarkable scattering in data, especially in Al-15%Si and B390 alloys.

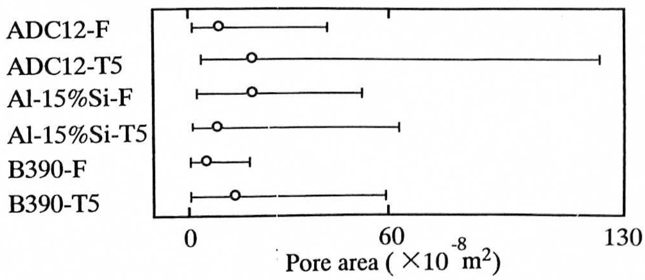


Fig.2. Areas of pore near crack initiation sites on the fracture surfaces after the fatigue tests.

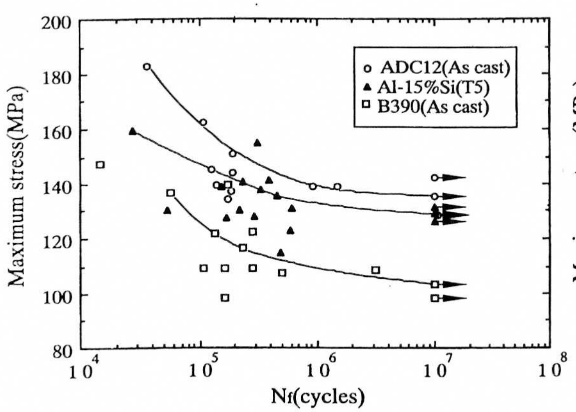


Fig.3. S-N_f curve of each alloy with the lower defect level.

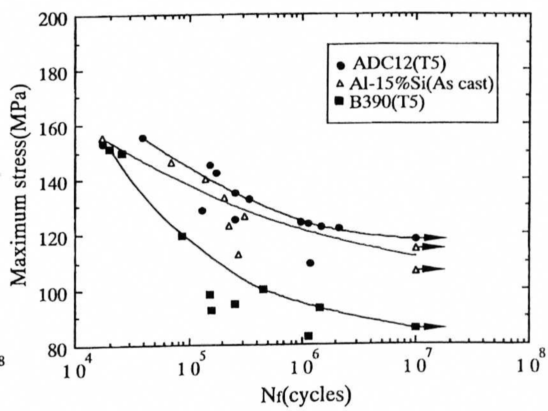


Fig.4. S-N_f curve of each alloy with the higher defect level.

SEM fractographs after the fatigue tests are shown in Fig.5. In ADC12 alloy, striation pattern is observed in a higher magnification micropraph. The propagation of a fatigue crack induces cleavage of eutectic Si particles. In Al-15%Si and B390 alloys, the cleavage fracture of primary Si and eutectic Si particles is not clearly observed. This structure has the appearance of deformed or smeared metal and its striation topography may be the result of damage that occurred during closure of

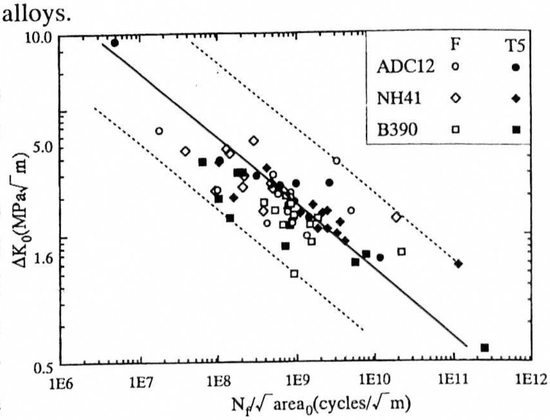


Fig.6. ΔK_0-$N_f/\sqrt{area_0}$ curves of each alloy.

the crack.

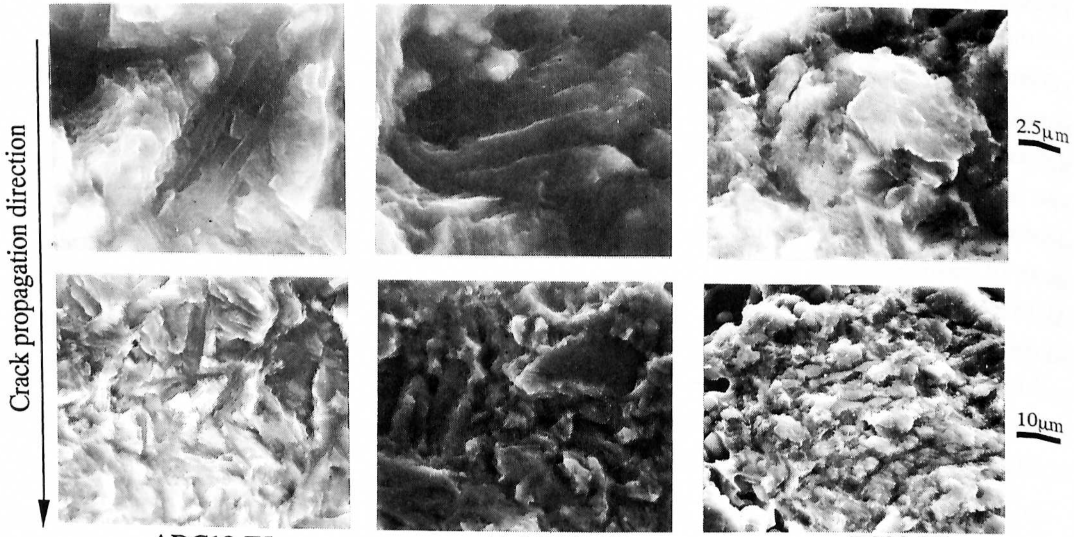


Fig.5. Fatigue fracture surfaces of the heat-treated(T5) alloys.

Kobayashi et al.[6] reported that the scattering of the S-N_f curves converged in case of appling ΔK_0-$N_f/\sqrt{area}$ fitting. In Fig. 6, the ΔK_0-$N_f/\sqrt{area}$ data for the different die cast alloys are plotted. It can be noted that for higher values of ΔK_0, the differences among the six curves with different silicon content and heat-treatment condition are small. Therefore, it is concluded that for the higher ΔK_0 region, the change of crack propagation rate is very small with changing the silicon content and heat-treatment condition.

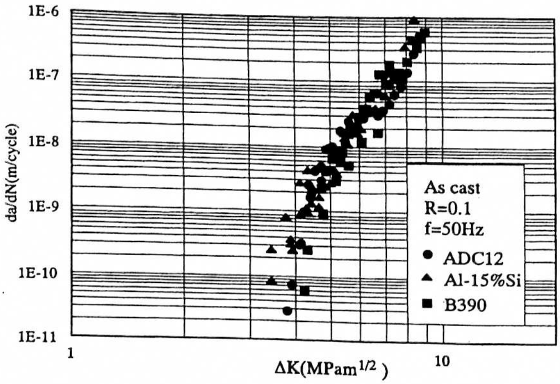


Fig.7. Relationships between da/dN and ΔK in the as-cast alloys.

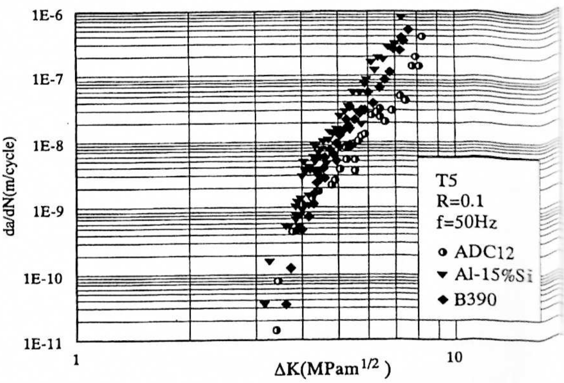


Fig.8. Relationships between da/dN and ΔK in the age-hardened alloys.

Results of fatigue crack growth tests for the three alloys are shown in Fig. 7 and Fig. 8. There curves are bi-linear with considerable changes in slop at about 10^{-9}m/cycle. The upper range is represented by the Paris power law relationship. The lower range is the near-threshold regime. A regression analysis on the log(ΔK) vs log(da/dN) data then yielded a value of ΔK_{th} and the Paris law coefficients and exponents for each test condition. The results of this regression analysis are summarized in Table 2. In as cast alloys, crack growth is the fastest in Al-15%Si alloy throughout the range tested. Crack growth is the slowest in ADC12-F alloy under the higher ΔK region. But crack growth is the slowest in B390-F alloy under the lower ΔK region. Fatigue crack deflection and branching in the near-threshold region with the increase of silicon content are observed, especially in B390-F alloy. In Al-15%Si-F alloy, it is considered that dislocation motion reduces slip reversibility and accelerate damage accumulation ahead of the crack tip because it contains many intermetallic compounds.

Table 2 Fatigue crack growth parameters.

Material		Threshold Stress Intensity Range $\Delta K_{th}(MPam^{1/2})$	Paris Coefficient (C)	Paris Exponent (m)
ADC12	As cast	3.92	1.23×10^{-12}	5.51
	T5	3.56	9.79×10^{-14}	6.62
Al-15%Si	As cast	3.27	1.29×10^{-14}	7.97
	T5	3.26	2.94×10^{-14}	8.18
B390	As cast	4.19	1.01×10^{-14}	8.20
	T5	3.70	3.88×10^{-15}	9.09

Fig. 9 shows the light micrographs of crack path in the near-threshold region. Crack branching and the cracking of primary Si particles near a main crack are shown in the case of higher Si content. An irregular crack path can reduce crack growth rate according to two mechanisms. Firstly, the length of microscopic crack path is longer than that of the macroscopically observed crack path. Therefore, surface area is wider when crack propagates, thereby, requires more work per unit of measured crack growth. Secondly, as the crack deviates, the local stress intensity or "driving force" in the mode I direction is effectively reduced and mode II component is generated.

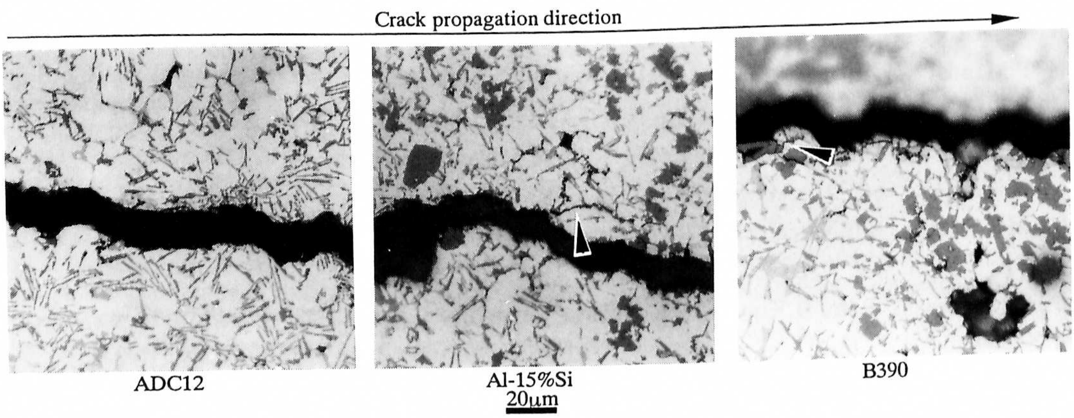


Fig.9. Light micrographs of crack path near Δk_{th} in as-cast alloys. Arrows show crack branching.

Fig. 10 shows SEM micrographs of the surfaces of fatigue specimens. Microcracks initiate at primary Si particles, β-Al_5FeSi and Al_2Cu intermetallic compounds ahead of a crack-tip. Fatigue cracks propagate along slip bands created in the vicinity of the crack tip, resulting in the eventual linkage of the microcracks.

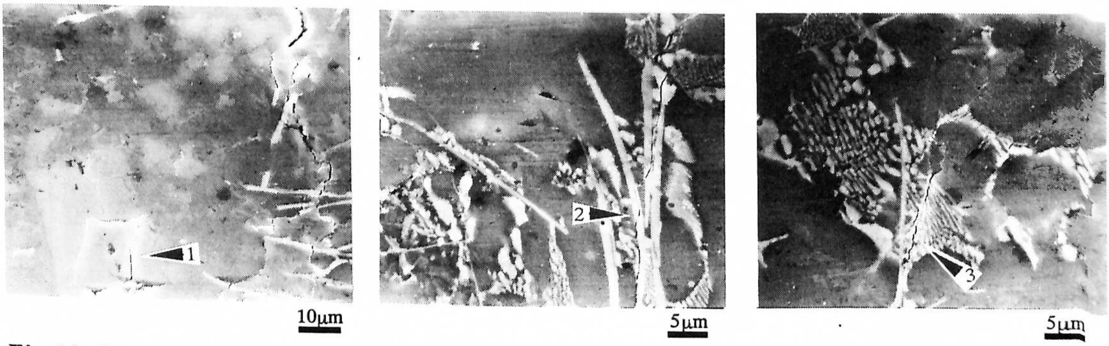


Fig.10. SEM micrographs of specimen surfaces after the fatigue tests. Arrows 1, 2, and 3 show microcracks at primary Si particle, β-Al_5FeSi and Al_2Cu intermetallic compounds particles, respectively.

4. CONCLUSIONS

1. The fatigue strength is largely dependent on the size and fraction of casting defect which becomes crack initiation sites. It increases with decreasing the size of casting defect and Si content. It is shown that the fatigue strength is insensitive to the aging treatment.
2. The relationship between fatigue life and casting defect was established using the ΔK_0-$N_f/\sqrt{area}$ relationship proposed by Kobayashi. In higher ΔK, fatigue crack growth show no significant difference with silicon content and application of aging treatment.
3. Fatigue crack growth rate decreases with increasing Si content in the low ΔK range. In this range, coarse primary Si decreases the crack growth rate by crack deflection and branching. In high ΔK range, however, the crack growth rate increases with Si content because the crack closure effect is vanishing.

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