FATIGUE CRACK GROWTH PROPERTIES OF Al-Si-Mg BASE CAST ALUMINUM ALLOYS

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ABSTRACT The fatigue crack growth behavior of an Al-Si-Mg base cast alloy has been investigated with special reference to the effect of solidification structure and aging condition. Fatigue crack growth tests have been performed under the constant load amplitude condition at a stress ratio of R=0.1 using a CT specimen. Crack closure was also investigated during the test. The aging condition influenced the da/dN-ΔK relationship little . However, significant difference was observed for crack closure levels. This suggests that intrinsic fatigue crack growth rates were influenced by aging conditions. Refining and spheroidizing of eutectic Si particles reduced the fatigue crack growth rates over a wide range of ΔK.

keywords: *fatigue crack growth, Ai-Si-Mg base cast aluminum alloy, solidification structure, age hardening, eutectic Si particles*

1. INTRODUCTION

The call for improved economy in connection with high reliability is the overriding requirement for the development of transportation machine. It is demanded that the structure should have a long life and low weight. Efforts are presently concentrated on a substantial reduction of the manufacturing costs for components and assemblies which completes the manifold demands.

Cast aluminum alloys have satisfied these requirements because of its high specific strength and low cost. But the more extensive use of cast aluminum alloys has been hindered mainly by the lower strength in comparison with forging alloys [1]. And very few researches have been done so far on not only tensile properties but fatigue properties. As well as the S-N curves, evaluation of fatigue crack growth properties is important to improve the reliability of cast Al alloy. In general, the microstructure of material has great influences on fatigue properties [2]. Therefore, the fatigue crack growth properties of the cast aluminum alloy should be investigated with special reference to the effects of solidification structure.

In the present study, fatigue crack growth tests are performed on the sand cast Al-Si-Mg base alloys with the solidified structures controlled by changing aging conditions and morphology of eutectic Si. The sand cast alloys were hot isostatic pressing treated (HIPed) to eliminate the influence of casting defects. This will be beneficial to highlight the effect of microstructure on the fatigue crack growth behavior.

2. EXPERIMENTAL

The study was carried out using JIS AC4CH(AA A356) aluminum alloys, which are representative heat-treatable Al-Si-Mg base cast alloys. In this alloy, the microstructure such as the size of solidification structure and morphology of eutectic Si can be easily controlled by changing casting condition and heat treatment. The shape of eutectic Si is spheroidized by adding Sr.

The melt was poured into sand mold and HIP treated to eliminate casting defects such as micro-porosities. Figure1shows the microstructures after solution treatment of each samples. It is shown that the eutectic Si is distributed around α −Al dendrite and internal voids are eliminated by HIP. Dendrite arm spacing is 60 μ m on average. Table1 shows the mechanical properties of both unmodified and Sr-modified samples.

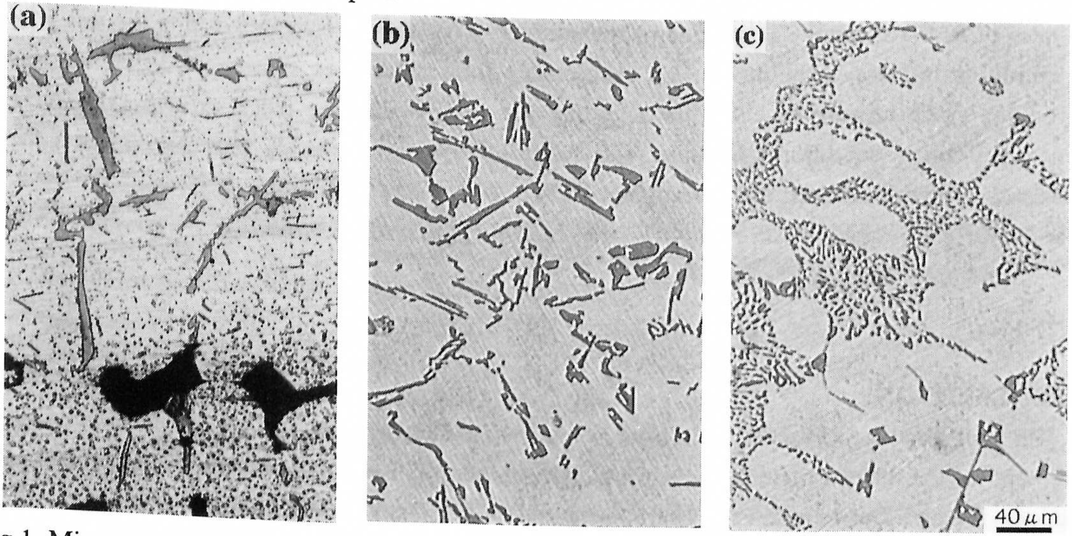

Fig.1 Microstructures of sand cast and solution treated A356 aluminum alloys with different eutectic Si morphology. (a) unmodified, nonHIP (b) unmodified, HIP (c)Sr- modified, HIP

Table1. Mechanical properties of the alloys

	UTS (MPa)	Yield Strength (MPa)	Elastic Modulus* (GPa)
Modified-UA	205	178	78
Modified-OA	217	190	101
Unmodified-UA	264	240	123

*Obtained by stress-strain relationship.

Compact tension (CT) specimens, with thickness (B) of 8.5mm and width (W) of 30mm were machined from the castings. The specimens were solution treated at 793K for 8h, water quenched, followed by natural aging at room temperature for 24h and were aged at 463K for 1h (under aged) and 20h (over aged) . Hereafter, these aging conditions are called, UA and OA, respectively.

To obtain the da/dN-ΔK relationship, fatigue crack growth tests were performed under constant load amplitude in general accordance with ASTM E647-93 using load control. All tests were performed under sinusoidal loading at a frequency of 10 Hz with a stress ratio of R=0.1 in room temperature. Crack length was measured by taking replica from the specimen surface. Crack closure was evaluated by compliance method [3]using a back face strain gauge. During a closure measurement, the frequency was reduced to 1 Hz. Figure 2 shows the block diagram of measurement system of the fatigue crack closure. Fractographical observations were performed using an SEM and crack growth paths were observed by an optical microscope.

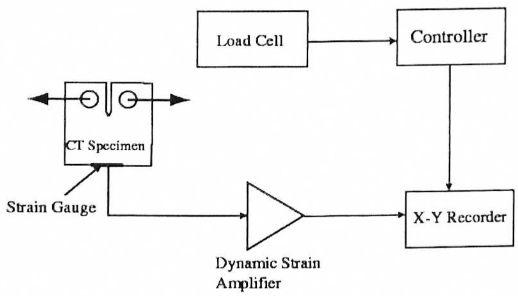

Fig.2 Block diagram of measurement system of the fatigue crack closure

3. RESULTS AND DISCUSSION

3.1 The effect of aging condition

The effect of aging conditions on fatigue crack growth was evaluated by the two different aging of UA and OA. They were both sand cast, Sr modified and HIP treated. Yield strength values obtained by monotonic tensile tests are comparable in these specimens. Figure 3 shows the da/dN-nominal ΔK curves for the two aging conditions. It can be seen that the fatigue crack growth rates are almost same for the two cases over the wide range of ΔK. The Paris exponent, m, was~9. But scattering in plots for UA is attributed to the crack-path tortuosity. Figures 4 (a) and (b) show the representative crack paths for the two aging conditions. The crack runs from left to right in the micrographs. It is found that crack meanders significantly in UA and crack propagates straight in OA.

Figure 5 shows the da/dN against the effective stress-intensity-factor range (ΔK_{eff}) which was calculated using applied nominal K_{max} and measured K_{cl}, i.e, $\Delta K_{eff}=K_{max}-K_{cl}$. The lower effective stress-intensity-factor range of UA may result from the larger crack closure. This is consistent with the significant crack meandering in Fig.4(a) in the sense that the meandering may enhance the crack closure. This point will be discussed later in more details.

The fracture surface observation revealed the faceted structure consisting of slip steps for both aging conditions in the low ΔK regime. The size of facet corresponds to a dendrite cell size. Holes indicating decohesion of Si particles were also observed inter - dendritic region. For UA, the fatigue fracture surface was covered with the oxide products, implying that numerous contacts of the fractured surfaces were repeated in association with the roughness-induced crack closure. In the Paris regime, an irregularity of fracture surface became more significant. However, striation was also observed within the macroscopically plateau region of the fractured surfaces. For UA, the oxides were still observed in this ΔK regime. In the higher ΔK regime, lots of dimples nucleated at the eutectic Si particles were observed in addition to the facets for the both aging conditions.

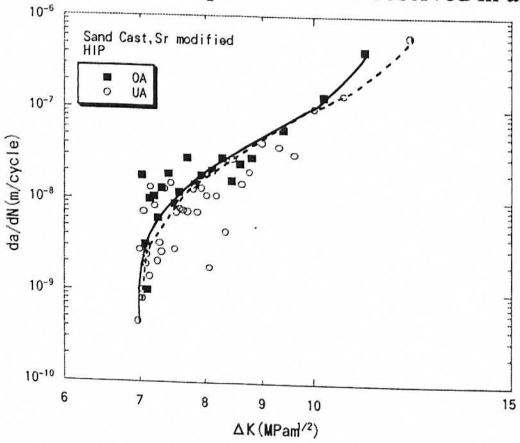

Fig.3 Fatigue crack growth rate (da/dN) vs. nominal stress-intensity-factor range (ΔK) for the sand cast A356 alloys, UA and OA.

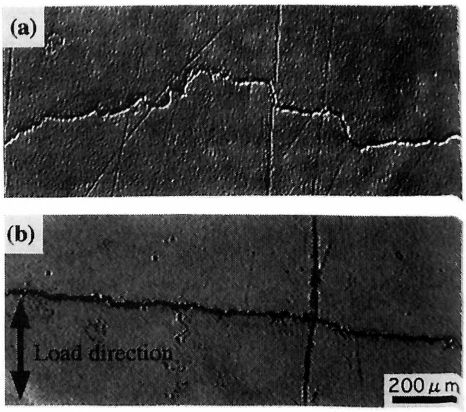

Fig.4 Fatigue crack path for the sand cast A356 alloys, (a) UA and (b) OA

For UA, the matrix is strengthened by G.P. zones coherent with matrix and shearable by dislocations. Significant plane slip occur when dislocations shear precipitates in the plastic zone ahead of a crack tip[4,5]. It is considered that this results in a crack-path tortuosity in UA. In contrast, for OA the strengthening is achieved by precipitation of intermediate β'phase incoherent with matrix and impenetrable by dislocations[6]. More homogeneous slip may occur in this case. This results in a straight crack path in OA.

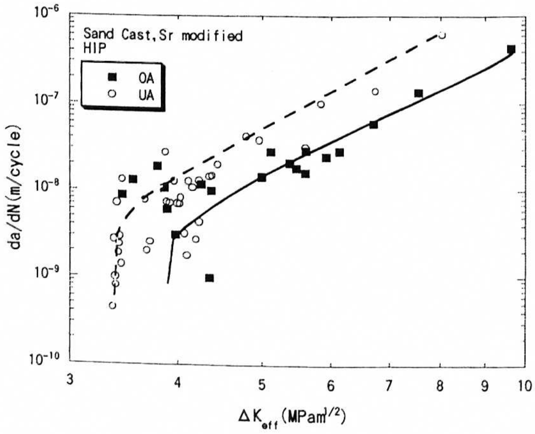

Fig.5 Fatigue crack growth rate (da/dN) vs. effective stress-intensity-factor range (ΔK_{eff}) for the sand cast A356 alloys, UA and OA.

3.2 The effect of eutectic Si morphology on fatigue crack growth

Figure 6 shows da/dN- Δ K curves of Sr-modified and unmodified UA specimens, respectively. Near threshold regime, fatigue crack growth rates of the two alloys are almost same, but in the Paris and the higher ΔK regimes, the growth rate of modified alloy is seen to be higher than the unmodified alloy's. The Paris exponent, m is ~9 for the modified alloy and ~6 for the unmodified alloy, respectively. And the rapid growth to failure is seen above $\Delta K=11MPam^{1/2}$ for the unmodified alloy. The higher crack growth rate for modified alloy over a wide range can be explained in terms of the larger crack opening displacement due to the reduced yield stress and elastic modulus. The crack tip opening displacement (CTOD) in plane strain condition is given by[7],

$$CTOD = \frac{K_{\max}^{2}}{2E\sigma_Y} \qquad (1)$$

where K_{max} is the maximum stress intensity factor , E is the Young's modulus and σ_Y is the yield stress. The values of E and σ_Y for the modified alloy are smaller than those for the unmodified alloy (see Table1). Therefore the CTOD value for a given ΔK is larger in the modified alloy. Since the CTOD per cycle is equivalent to the crack growth rate in a cyclic deformation, it appears natural that the modified alloy has shown higher crack growth rate. When da/dN is plotted against ΔK_{eff} instead of ΔK, the crack closure level, i.e, $K_{cl}-K_{min}=\Delta K-\Delta K_{eff}$, is nearly almost same for the modified and unmodified specimens. Therefore, equality of K_{cl} for the two cases imply that Si particle morphology does not influence the crack closure significantly.

The size of plastic zone ahead of the fatigue crack tip was calculated at $\Delta K=11MPam^{1/2}$. When a plastic zone size is sufficiently small, it is given by[7],

$$\omega = \frac{1}{3\pi}\left(\frac{K_{\max}}{\sigma_Y}\right)^2 \qquad (2)$$

under plain strain condition. Substitution of K_{max} and σ_Y values into eq.(2) yields $\omega \fallingdotseq 280\mu m$ for the unmodified alloy and $500\mu m$ for the modified alloy. These sizes exceed the dendrite arm spacing of $60\mu m$, which means that a plastic zone includes several dendrite cells at $\Delta K=11MPam^{1/2}$. In such a high stress condition, eutectic Si particle morphology located at inter-dendritic region may influence the cyclic deformation behavior. This is in contrast to the crack growth at low stress levels, where a small plastic zone tends to propagate through Al matrix without feeling the effect of eutectic Si.

As shown in Fig.6, crack growth rate in the modified alloy increased linearly, while it acceralated in the unmodified alloy above $\Delta K=11MPam^{1/2}$. The crack growth rate in this regime may be affected more strongly by the ductility and stress concentration. The ductility in the monotonic tensile tests is known to be larger for the modified alloy than for the unmodified alloy. The good ductility for the modified alloy was also noted in the fracture surface with dimples. In view of the stress concentration, the larger value of ω in the modified alloy may be favored in suppressing the crack propagation.

From the microstructural point of view, Si particle do not deform with matrix. Then, cracked or decohered particles serve as nucleation sites for voids which eventually lead to fracture of the alloy[8]. But spheroidizing and refinement of Si particle decrease a stress concentration at the interface of particle/matrix, hindering decohesion or cracking of Si particles, contributing to the good ductility in the modified alloy.

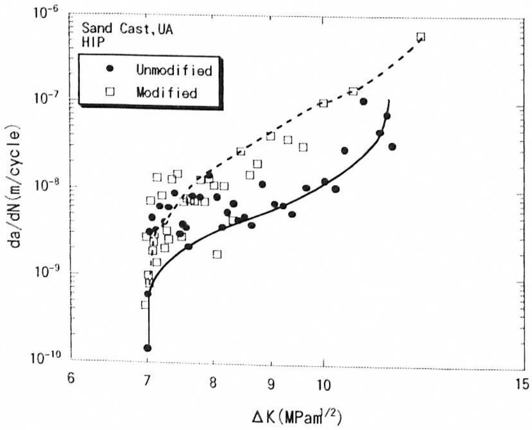

Fig.6 Fatigue crack growth rate (da/dN) vs. nominal stress-intensity-factor range (ΔK) for the sand cast A356 alloys, Sr-modified and unmodified.

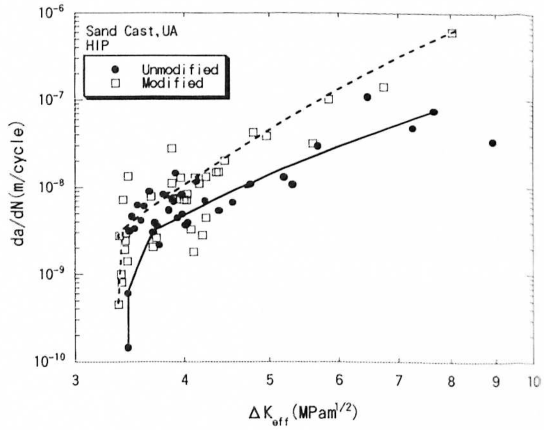

Fig.7 Fatigue crack growth rate (da/dN) vs. effective stress-intensity-factor range (ΔK_{eff}) for the sand cast A356 alloys, Sr-modified and unmodified.

4. CONCLUSIONS

Fatigue crack growth behavior of a Al-Si-Mg base cast alloy was examined. The fatigue crack growth depends both on the aging condition and the eutectic Si particle morphology. And the fatigue crack growth rate was smaller in the under aged specimen (UA) when da/dN was plotted against ΔK_{eff}, while it was same the under and over aged specimens in the da/dN vs. ΔK plot. This change can be attributed to the significant crack closure contribution in the UA. Refining and spheroidizing of eutectic Si particles increased the fatigue crack rates, but improved the resistance in high ΔK regime.

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