Effects of Dendrite Cell Size and Eutectic Si Particle Morphology on Fatigue Crack Growth in Cast and HIPed AC4CH Alloys

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Fatigue crack growth tests were performed for structurally controlled AC4CH cast alloys. Elimination of casting defects from the casts was achieved by means of post-casting HIP treatment. Compliance change measurement was made during the fatigue crack growth test to investigate crack closure. The level of crack closure was comparable among the alloys with different microstructure. Spheroidizing and refining of the eutectic Si particles are essential in terms of reduced propensity of particle fracture, which results in prolonged stable crack growth region of the $da/dN-\Delta K$ relationship and improved fatigue crack growth resistance at the high ΔK . At low ΔK , however, the fatigue crack growth rate is controlled by general matrix strength. The higher proof stress due to the irregular shaped Si particles and fine dendrite cell size results in the reduced crack opening displacement of each fatigue cycle or the reduced crack growth rate.

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I. Introduction

Aluminum alloy castings have become a viable alternative in structural applications for ground vehicles. With improvements in casting quality and the potential economic advantage, they are being considered even for primary aircraft structure applications which carry significant flight loads. Improved fatigue resistance is required for the cast alloys in such nontraditional use. The Al-Si-Mg based JIS AC4CH (AA A356) alloys are most commonly used for the applications. The alloys are dual-phase systems consisting of primary aluminum dendrites and the interdendritic eutectic Si phase. Silicon provides age-hardening with the help of magnesium to form the Mg_2Si strengthening precipitate. The microstructural features that most strongly affect mechanical properties are dendrite arm spacing and morphology of eutectic Si particles. When undesirable trace elements (especially iron) are present, large acicular intermetallic compounds may be present and they reduce ductility significantly. However, so-called casting defects such as shrinkage, gas porosity, and non-metallic inclusions are more crucial for fatigue properties⁽¹⁾.

It has been reported that elimination of casting defects, such as internal voids by hot isostatic pressing (HIPing) has a generally favorable effect on the smooth-bar fatigue life of Al-Si-Mg base alloys⁽¹⁾. But in the HIPed alloy, fatigue crack initiation from active slip planes in dendrite cells or damaged eutectic Si particles was observed instead of pre-existing casting defects⁽²⁾. In such situation conventional life prediction method is no longer applicable because most of them are based on the

size and morphology of the casting defects. This means that we need to pay much more attention to the effects of characteristic solidification microstructure on fatigue properties with improvements in casting quality.

As well as examining fatigue life, evaluation of fatigue crack growth properties is important to improve reliability of the cast alloys, in particular from the standpoint of damage tolerant design. It is known for cast alloys that crack deflection and the resultant roughness induced crack closure commonly occur and influence $da/dN-\Delta K$ relationships significantly⁽³⁾⁻⁽⁵⁾. Therefore how the crack closure affects the fatigue crack growth should be examined to recognize the microstructural effect on *intrinsic* fatigue crack growth behavior. In the present study, constant load amplitude fatigue crack growth tests including fatigue crack closure measurement were performed for the cast and HIPed AC4CH alloys to examine the effects of characteristic solidification microstructure on fatigue crack growth.

II. Experimental Procedures

1. Materials

Materials used in the present study are JIS AC4CH cast aluminum alloys. Castings were fabricated at the Advanced Materials Research Laboratory, Hitachi Metals, Ltd. The materials were melted at 993 K and cast into the sand mold and the permanent mold located in the pressure vessel. The melt was cooled under a 1 MPa pressure. The size of the resultant castings were $170 \times 120 \times 16$ (mm³) for the sand mold cast and $200 \times 100 \times 20$ (mm³) for the permanent mold cast. For some castings, strontium was added to the melt just before casting. This modification treatment caused mor-

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phological change in eutectic Si particles, as will be shown later. The resultant castings were HIPed with the applied pressure of 100 MPa over a period of 1 h at 773 K in Ar atmosphere to reduce casting defects such as shrinkage and porosities. Chemical composition of the casts after HIPing was 7.12%Si, 0.37%Mg, 0.10%Fe, 0.14%Ti and bal. Al (mass%). The modified casts also included 70~110 ppm strontium.

The important microstructural features of the present materials are primary aluminum dendrites and interdendritic eutectic Si particles. Both the dendrite size and the morphology of the eutectic Si particles depend heavily on processing parameters such as solidification rate, the presence of chemical modifiers, and solution heat treatment. Microstructural fineness is related to the size of the dendrites and the Si particles. Fineness is evaluated by the dendrite cell size, which is comparable to dendrite arm spacing (DAS). Silicon particles are characterized by an aspect ratio.

Representative microstructures of the present materials are shown in **Fig. 1**. They are those after solution heat treatment at 793 K for 8 h. Figure 1(a) shows the typical example of the un-HIPed alloy. Porosities are observed

at the inter-dendritic region. While, for the HIPed castings (**Fig. 1(b) to (d)**), which were used in the present study, very few casting defects are observed. These are; (b) modified and sand mold cast, (c) un-modified and sand mold cast, and (d) modified and permanent mold cast materials. The (b) and (c) have comparable dendrite cell size of 60 μm , but different Si particle morphology. The average values of aspect ratio were 1.3 for globular Si particles in (b) and 7 for irregular needle-like Si particles in (c). The (b) and (d) have comparable Si particle aspect ratio of 1.3, but different dendrite cell size. It was 20 μm for (d). It should be mentioned that the average Si particle size is smaller in (d) than (b) since the higher cooling rate to achieve fine dendrite size also reduce Si particle size. In addition to these materials the un-modified and permanent mold cast material was also prepared, whose dendrite cell size and Si particle aspect ratio are 20 μm and 6, respectively. Hereafter the materials with microstructures shown in (b), (c) and (d) are called CG (Coarse dendrite cell and Globular Si), CN (Coarse dendrite cell and Needle-like Si), FG (Fine dendrite cell and Globular Si), respectively. There is an additional material having a structure called FN (Fine den-

Fig. 1 Optical micrographs of the AC4CH cast alloys after solution heat treatment at 793 K for 8 h. (a) modified and sand mold cast but un-HIPed, (b) modified, sand mold cast and HIPed, (c) un-modified, sand mold cast and HIPed and (d) modified and permanent mold cast and HIPed.

drite cell and Needle-like Si). The effects of dendrite cell size and Si particle morphology on fatigue crack growth and tensile properties can be revealed by comparative examination among those materials.

2. Heat treatment

The HIPed castings were cut into rectangular bars with shoulders (gauge section: $16 \times 5 \times 4 \text{ mm}^3$) for tensile tests and compact tension (CT) specimens (thickness: 8.5 mm, width: 30 mm) for fatigue crack growth tests. They were solution treated at 793 K for 8 h and water quenched. After holding at a room temperature for 24 h, the specimens were aged at 463 K for 20 h. This is the slightly overaged condition referring to the age hardening curves obtained in advance⁽⁶⁾.

3. Tensile tests and fatigue crack growth tests

Monotonic tensile tests were performed using an Instron type testing machine at a constant strain rate of $8.3 \times 10^{-5} \text{ s}^{-1}$ at a room temperature in air. Constant load amplitude fatigue crack growth tests were performed in general accordance with ASTM E647-93. The tests were made using a servo-hydraulic testing machine under sinusoidal wave form at a frequency of 10 Hz with a stress ratio of $R=0.1$. Crack length measurement was made both by taking replica from the specimen surface and monitoring a compliance change of the specimen using a back-face strain gauge. Crack closure was also evaluated by the compliance method. During the closure measurement, the test frequency was reduced to 0.01–0.1 Hz. Crack growth path on the specimen surface was observed using an optical microscope. Fractographical observation was made using a SEM.

III. Experimental Results

1. Monotonic stress-strain curves

Representative stress-strain curves are shown in Fig. 2 for comparison. The CN with the large dendrite cell size and the coarse needle-like Si particles exhibits higher proof stress, large work hardening, and very little elongation. Spheroidizing of Si particles in the CG slightly reduces strength but increases ductility. Reduced dendrite cell size for FG and FN results in larger UTS and significantly larger ductility. The strength is higher in FN with needle-like Si particles and the elongation is larger in FG with spheroidized Si particles. Mechanical properties obtained are shown in Table 1.

2. Fatigue crack growth rates

Figures 3 shows $da/dN-\Delta K$ relationships of four specimens. For the comparison between CG and CN with the same dendrite cell size, CN (containing needle-like Si particles) exhibited smaller fatigue crack growth rates than CG. However, CN reached the final fracture at the smaller ΔK . This holds true for comparison between FG and FN with finer dendrite cell size. FN with needle-like Si particles exhibited smaller growth rates over a wide

Table 1 Tensile properties of the AC4CH cast alloys with different microstructures; CG, CN, FG and FN.

Materials	$\sigma_{0.1}$ /MPa	$\sigma_{0.2}$ /MPa	UTS/MPa	Elongation (%)
CG	175	190	217	1.9
CN	237	264	268	0.5
FG	190	201	253	12.9
FN	200	216	268	6.1

Fig. 2 Representative stress-strain curves for the AC4CH cast alloys with different microstructures; CG (Coarse dendrite cell and Globular Si), CN (Coarse dendrite cell and Needle-like Si), FG (Fine dendrite cell and Globular Si) and FN (Fine dendrite cell and Needle-like Si).

Fig. 3 $da/dN-\Delta K$ relationships of four AC4CH cast alloys; CG, CN, FG and FN.

range of ΔK but rapid increase of the growth rate at the smaller ΔK than FG. Finer dendrite cell size of FN and FG provided the overall reduced crack growth rate rather than CN and CG. The Paris exponent m , which is the gradient of the linear region of the $da/dN-\Delta K$ curve, was smaller and stable crack growth was extended to the higher ΔK in FN and FG.

3. Crack closure

Figure 4 shows typical load-back-face strain curves for the specimen containing an artificial notch and one containing a fatigue crack with the same crack length.

Fig. 4 Typical load—back-face strain curves for the specimen containing an artificial notch and one containing a fatigue crack with the same crack length.

Fig. 5 Change in compliance with crack length for the artificial notched specimen and the fatigue cracked specimen.

The curve was recorded on the way of load reduction. Linear relationship with a constant gradient (this gives compliance) was obtained for the artificial notch. While, the curve bends at a certain load level below which it gives a larger compliance for the fatigue crack. **Figure 5** shows change in compliance with crack length for the artificial notched specimen and the fatigue cracked specimen. For the latter the compliance was obtained using the initial linear region at the high load range in Fig. 4. Both curves fit well. This indicates that the fatigue crack is fully opened at the high load range. The increase of the gradient in the load—back-face strain curve for the specimen containing the fatigue crack in Fig. 4 is due to the apparent reduction of crack length by the mutual contact of fatigue crack surface. This is the evidence of crack closure. The stress intensity factor for closure, K_{cl} is obtained from the load at which deviation starts, P_{cl} and the crack length, a .

Figure 6 shows the relationship between the K_{cl}/K_{max} and ΔK for four specimens. If there is no closure, K_{cl} can be replaced by K_{min} and then $K_{cl}/K_{max} = 0.1$. The K_{cl}/K_{max} value decreased from 0.6 at ΔK of $8 \text{ MPa}\sqrt{\text{m}}$ to 0.3 at ΔK of $17 \text{ MPa}\sqrt{\text{m}}$ (but only for FG). No large and sys-

Fig. 6 Relationship between the K_{cl}/K_{max} and ΔK of four AC4CH cast alloys; CG, CN, FG and FN.

Fig. 7 Tensile fracture surface of the AC4CH cast alloys. (a) CN and (b) CG.

tematic difference can be observed among the specimens with different dendrite cell size and Si particle morphology.

4. Fractography

Tensile fracture surface of CN and CG are shown in **Fig. 7(a)** and **(b)**. No mark of the casting defects as the initiation site of the fracture was left in the present HIPed castings. Cracked and decohered coarse eutectic

Fig. 8 Fatigue fracture surfaces of the AC4CH cast alloys formed at various ΔK conditions. Macroscopic crack growth direction is indicated by arrows. (a) CG ($\Delta K=8 \text{ MPa}\sqrt{\text{m}}$) (b) FG ($\Delta K=8 \text{ MPa}\sqrt{\text{m}}$) (c) CG ($\Delta K=17 \text{ MPa}\sqrt{\text{m}}$) (d) CN ($\Delta K=11 \text{ MPa}\sqrt{\text{m}}$).

Si particles were evident in the CN. Relatively flat cleavage-like appearance corresponds to the region in which inter-dendritic cell fracture took place. While, dimple structure originating from the cracked Si particles was observed in the CG although the depth of dimples was shallow. Large Al-Si-Fe intermetallics were observed in both specimens. The FG and FN exhibited similar fracture surface to the CG and CN, respectively.

Fatigue fracture surfaces formed at various ΔK conditions are shown in Fig. 8. At low ΔK ($\Delta K=8 \text{ MPa}\sqrt{\text{m}}$) fatigue fracture surface is covered with large number of slip steps as shown in (a) and (b). The fracture surface can be divided into the units of area on the basis of the family of slip steps. The size of the unit area corresponds to the dendrite cell size, *i.e.*, $60 \mu\text{m}$ for CG and $20 \mu\text{m}$ for FG. The FG with fine dendrite cell size and globular Si particles exhibited striations on the fracture surface at high ΔK as shown in (c). However, the striations were formed in a very limited area for CG. For the CN containing coarse needle-like Si particles fatigue fracture surface is covered with cracked and decohered Si particles in (d), which is comparable to the monotonic tensile fracture surface shown in Fig. 7(a).

IV. Discussion

1. Intrinsic fatigue crack growth behavior of AC4CH cast alloys

In the present study the occurrence of crack closure was readily detectable using the conventional load and back-face strain gauge outputs as shown in Fig. 4. The gradient of load—back-face strain relationship or compliance showed remarkable change as decreasing the applied load. Estimated crack length from the compliance below the P_{cl} (K_{cl}) was rather short (by several thousand μm order) compared to the actual crack length. This suggested that the crack face contact took place throughout a wide range of crack surface far from the actual fatigue crack tip.

The result of closure measurement as shown in Fig. 6 indicates that the degree of crack closure is independent on the microstructural variation prepared in the present study. Observed fatigue fracture surface and crack path at the specimen surface revealed that the crack deflection in the present material was fairly complicated and exhibited three dimensional variation. Various patterns of crack deflection were produced by transgranular (dendrite cell) crack growth, crack extension through the fractured Si particles or along the matrix/Si particle interface, linking between the main crack and micro-cracks formed ahead of the main crack tip.

Crystallographic crack path in the under-aged precipitation-hardened aluminum alloys has been recognized as the origin of crack deflection and resultant roughness-induced crack closure⁽⁷⁾. In this case, the matrix consists of coherent precipitates such as GP zone. These strengthening precipitates are sheared by slip bands ahead of a fatigue crack and result in heterogene-

Fig. 9 $da/dN-\Delta K_{\text{eff}}$ relationships and the original $da/dN-\Delta K$ curves for four AC4CH cast alloys; CG, CN, FG and FN.

ous deformation. The resultant single shear failure promotes a highly serrated and tortuous crack path. In the present study, the effect of precipitates in the matrix is considered to be negligible for the following reasons.

(i) The matrix was over-aged (OA). Major precipitates of the present alloy system in the OA condition are incoherent β' and residual GP zone. Presence of the incoherent precipitates in the matrix suppresses the single slip and formation of tortuous crack path.

(ii) Even if the matrix was under-aged serrated and tortuous crack path was not observed in the present materials due to the dispersed eutectic Si particles.

(iii) The effect of slip characteristics is evident for near-threshold fatigue crack growth.

The present study was concerned with fatigue crack growth in the so-called Paris region (II_b region), in which the crack growth behaviour is relatively insensitive to the aging condition.

Similar crack growth path and crack face topography for all specimens resulted in the comparable crack closure level as shown in Fig. 6. Referring to the crack closure level in Fig. 6 $da/dN-\Delta K$ relationships in Fig. 3 were converted into $da/dN-\Delta K_{\text{eff}}$ relationships ($\Delta K_{\text{eff}} = K_{\text{max}} - K_{\text{cl}}$) and they are shown with the original $da/dN-\Delta K$ curves in Fig. 9. The $da/dN-\Delta K_{\text{eff}}$ relationships give us the idea how dendrite cell size and Si particle morphology affect the *intrinsic* fatigue crack growth of the present materials.

2. Effects of dendrite cell size and eutectic Si particle morphology on fatigue crack growth rates

It is usually difficult to consider the effects of dendrite cell size and eutectic Si particle morphology separately. Because the casting procedures taken to achieve fine dendrite cell size also refine eutectic Si particle size although the aspect ratio can be controlled by means of chemical modification. Keeping this limitation in mind, the two effects will be discussed in this section.

Eutectic Si particle morphology in the AC4CH alloys influences the fatigue crack growth rate differently depending on the applied stress intensity range, ΔK . For example, unmodified needle-like Si particles reduce crack growth rates at the low ΔK region, but accelerate crack

growth rates at the high ΔK region. The former can be related to large monotonic and cyclic strain hardening in the material containing the coarse needle-like Si particles.

As shown in Fig. 2 un-modified needle-like Si particles are responsible for higher proof stress and larger work hardening regardless of difference in size of dendrite cell and Si particles. It is generally known that the shape of the secondary phase exert a substantial influence on the strength of the alloy for a given amount of secondary phase, eutectic Si in this case⁽⁸⁾. Dislocation motion in a particular direction will be impeded by Si particles. Flattening particles (shifting particle morphology from globular to needle-like or plate-like) increases the interference with dislocation motion. The mean free path of dislocations would be smaller in the matrix containing needle-like Si particles and hence proof stress would be higher.

Caceres *et al.*⁽⁹⁾ also studied the tensile properties of Al-7%Si-0.4%Mg casting alloys as a function of dendrite cell size and Si particle aspect ratio for unmodified and Sr-modified material. They showed that the morphology and distribution of Si particles control strain hardening in this materials and reported larger strain hardening for coarser unmodified structures than the finer ones, either unmodified or Sr-modified. Their results are in good agreement with the present work. The present authors also examined cyclic hardening behavior of the present materials under various constant plastic strain amplitude conditions and revealed that the unmodified material exhibited larger cyclic strain hardening and larger cyclic flow stress than the modified one⁽⁶⁾.

Concerning the effect of dendrite cell size on monotonic tensile properties, previous works by the present authors revealed that Hall-Petch type relation holds true between the proof stress and dendrite cell size for AC4CH alloys containing modified globular Si particles⁽¹⁰⁾. Decrease in dendrite cell size increases proof stress. This statement is considered to be correct although we cannot see this fact clearly in Fig. 2 and Table 1 since the effect of Si particle morphology is overlapped.

As shown in Fig. 9, FN and FG with finer dendrite cell size exhibit reduced *intrinsic* crack growth rates compared to CN and CG. In addition to that, FN and CN containing needle-like unmodified Si particles exhibit reduced *intrinsic* crack growth rates compared to FG and CG although this is limited to the low ΔK_{eff} region for CN for the reason mentioned later.

In the present study, near-threshold fatigue crack growth rate has not been treated. The $da/dN-\Delta K$ relationships shown in Fig. 3 and Fig. 9 correspond to fatigue crack growth in so-called II_b and II_c region. Crack growth rate in the Paris regime is often described by the geometrical model which has been developed by many researchers⁽⁷⁾. This model is based on the geometrical relationship between the striation spacing and the crack tip blunting process. Experimental correlations of striation spacings with crack growth rates are also a fun-

damental base of the model. As shown in Fig. 8(c) striations were formed in the present alloys and their spacings were comparable to the crack growth rates of the corresponding ΔK (ΔK_{eff}). The cyclic crack tip opening displacement $\Delta\delta$ is related to the ΔK by eq. (1).

$$da/dN \cong \Delta\delta \cong C(\Delta K)^2/(\sigma_Y E') \quad (1)$$

where, σ_Y is the cyclic proof stress, E' is Young's modulus in plane strain, and C is a function of yield strain, cyclic strain hardening exponent, the efficiency of blunting and re-sharpening in fatigue, and the numerical constant. This model means that da/dN is inversely proportional to σ_Y . Therefore increased σ_Y will reduce the crack growth rate.

It is concluded from these arguments that fatigue crack growth rates of AC4CH cast alloys can be reduced by needle-like un-modified eutectic Si particles and refined dendrite cell, both of which contribute to increase monotonic and cyclic proof stress. The effect of increased proof stress may work effectively for crack growth rate reduction if Si particles suffer no damage. However, fracture and decohesion of eutectic Si particles definitely occurred, in particular at low ΔK levels in CN.

Once fracture or decohesion of Si particles occurs ahead of the crack growth front, this contribution for increasing crack growth rate seems to be much larger than the proof stress effect for crack growth rate reduction. In this case a propensity for fracture and decohesion of particles is considered to dominate the crack growth mechanism and the resultant fatigue crack growth rates. Caceres *et al.*⁽¹¹⁾ examined the cracking of eutectic Si particles in Al-7%Si-0.4%Mg cast alloys during plastic deformation. They found that the larger and longer (larger aspect ratio) particles are more prone to cracking. In coarser structures (with larger dendrite cell size) particle cracking occurs very rapidly at low strains, while in finer structures (smaller dendrite cell size) the progression of particle cracking is more gradual. Coarse and needle-like un-modified eutectic Si particles in CN will act as stress risers and easily crack or decohere providing multiple cracks and accelerate crack growth rates even at a relatively low ΔK (low K_{max}) condition. Therefore, in contrast to that the reduced fatigue crack growth rate is attained in FN than FG in the wide range of ΔK_{eff} , the ΔK_{eff} range in which CN shows the reduced crack growth rate is restricted to that below $5 \text{ MPa}\sqrt{\text{m}}$.

The specimen FG exhibited a slow stable crack growth (Fig. 9) and striations on the fatigue fracture surface (Fig. 8 (c)). Striation formation during fatigue crack growth reflect the reduced possibility of fracture and decohesion of the eutectic Si particles ahead of the fatigue crack growth front. Sheroidizing and refining of the eutectic Si particles is essential in terms of reduced propensity of particle fracture, which results in improved

fatigue crack growth resistance at the high ΔK range.

V. Conclusions

Fatigue crack growth tests were performed for sand mold cast and permanent mold cast AC4CH alloys which were conditioned to give different dendrite cell size, eutectic Si particle morphology. Elimination of casting defects from the casts was achieved by means of post-casting HIP treatment to highlight these microstructural effects. Compliance measurement using back-face strain gauge through the fatigue crack growth tests indicates high crack closure levels of the present cast materials. Fatigue crack surface far from the crack growth front is still suffering from mechanical contact. This is attributed to the large roughness induced crack closure effect. Since crack closure contributions were comparable among all the specimens, it can be considered that the present experimental results explain effects of dendrite cell size and eutectic Si particle morphology on the *intrinsic* fatigue crack growth property of the cast AC4CH alloys. Coarse and needle-like un-modified eutectic Si particles act as stress risers and easily crack or decohere to provide multiple cracks, and accelerate crack growth rates at high ΔK . While, in the low ΔK , the un-modified cast showed lower crack growth rate. This is due to the larger proof stress to reduce the cyclic crack opening displacement. Striation formation during fatigue crack growth reflects the reduced possibility of fracture and decohesion of the eutectic Si particles ahead of the fatigue crack growth front. Sheroidizing and refining of the eutectic Si particles are essential in terms of reduced propensity of particle fracture, which results in prolonged stable crack growth region and improved fatigue crack growth resistance at the high ΔK .

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