Notch Size Effects in the Fatigue Characteristics of Al-Si-Cu-Mg Cast Alloy*¹

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Influences of the microstructure, micro defects and the stress concentration factor on fatigue characteristics were investigated for a JIS-AC4B alloy containing 6.79%Si, 2.93%Cu, 0.17%Mg and 0.59%Fe, and for an iron free Al-Si-Cu-Mg alloy. Solidification microstructures consist of dendritic α phase, eutectic Si, Al_2Cu and Mg_2Si phases in both alloy specimens and a few gas and shrinkage porosities appear in every specimen; while Fe compound modified by Mn appears among the dendrites in the AC4B alloy. Rotating bending fatigue tests were carried out on specimens with notches of 2, 1, 0.3 and 0.1 mm radius. Both AC4B and Al-Si-Cu-Mg alloys show the same fatigue sequence when the notch size is larger than 1 mm, indicating that the gas and shrinkage porosities act as the origins of cracking and thus govern the fatigue characteristics. Contrarily, when the notch radius becomes smaller than 0.3 mm, so that the stress concentration factor becomes larger than 2.4, the AC4B alloy has a higher fatigue strength than the Al-Si-Cu-Mg alloy, indicating that Fe-compounds may retard crack propagation.

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1. Introduction

The use of light cast aluminum alloys is increasing, particularly in the transportation industry, for energy conservation and environmental protection. Al-Si-Cu-Mg cast alloys have superior strength and wear resistance, and are thus used in a multitude of automotive parts such as wheels, crank cases, cylinder heads and pistons.^{1,2)} AC4B alloy is defined 7–10%Si and 2–4%Cu as its primary components, and its solidified structure consist of dendritic α -phase, eutectic Si and Al_2Cu . However, the maximum allowable Fe composition is 1.0%, and that Fe compounds such as $\alpha\text{-Al}_{15}(\text{Fe}, \text{Mn})_3\text{Si}_2$ or $\beta\text{-Al}_5\text{FeSi}$ crystallize in this alloy. It is reported that these compounds may then act as a crack source, thus reducing strength and ductility.^{3–7)} These phases might also increase the possibility of fatigue fracture under repeated stresses. Furthermore, in general, mechanical components have rough surfaces and therefore stress concentrates are often present. It is necessary to clarify the influence of the microstructure and the surface roughness on fatigue characteristics. However, the fatigue characteristics of Al-Si-Cu-Mg cast alloy have been only reported for smooth materials, and little research exists regarding notched cast materials.^{8,9)} Thus the present research investigates the influence of the solidification structure on the fatigue characteristics of notched AC4B alloy and a similar composition of high-purity Al-Si-Cu-Mg alloy specimens.

2. Experimental Procedure

In addition to commercially available Japan-industrial-standard AC4B alloy, high-purity Al-Si-Cu-Mg alloy (hereafter A4 alloy) of a composition equivalent to the AC4B alloy was used. The A4 alloy was prepared using 99.99%Al, 99.999%Si, 99.999%Cu, and 99.9%Mg. The materials were melted at 1003 K under 0.2 mass% flux ($5\text{MgCl}_2 +$

Table 1 Chemical composition of specimens. (mass%)

	Si	Cu	Mg	Mn	Fe	Zn	Ni	Pb	Sr	Al
JIS-AC4B	6.79	2.93	0.17	0.49	0.59	0.17	0.03	0.05	0.03	bal.
A4 (Al-Si-Cu-Mg)	6.73	2.72	0.15	—	—	—	—	—	0.03	bal.

$3\text{KCl} + 2\text{MgF}_2$) and degassing by Ar gas. Then 300 ppm of Sr was added to modify eutectic Si. After degassing, each melt was kept at 1003 K for 300 s, and then cast into a Y-shaped permanent mold with a thickness of 11 mm. The chemical compositions of the cast specimens are shown in Table 1.

Rectangular specimens with sizes of 10 mm, 10 mm and 62 mm were cut from these ingots and solution treatment was undertaken on each specimen in a salt bath at 773 K for 36 ks. The specimens were then quenched in ice water, and next subjected to ageing treatment at 433 K for 50.4 ks in a silicone oil bath to attain peak hardness. Fatigue test pieces were machined into the shapes and notches as shown in Fig. 1. The 60° V-shaped notches with radii, ρ , of 2, 1, 0.3 and 0.1 mm were formed using a notching bit. The surface of notch bottom was then polished using silicon carbide (800

Fig. 1 Schematic illustrations of fatigue specimen (a), and notch (b).

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Fig. 2 Microstructure of the A4 (Fe free Al-Si-Cu-Mg) alloy (a), and the AC4B alloy (b), after peak aging.

Fig. 3 Examples of gas porosity (a), and shrinkage porosity (b).

mesh), alumina powder (3 μm), and diamond paste (1 μm) to attain a mirror finish. An Ono-type rotating bending fatigue test was performed under conditions of a bending moment of 15 N·m, a rotation rate of 50 Hz and a two-way sine wave at a response ratio, R , of -1 . In this study, the nominal stress at the notched cross section was adopted as the applied stress, and the stress was varied at intervals of 5 MPa. The fatigue limit stress is determined as the maximum stress, where no failure occurs even over 10^7 cycles. The non-propagating cracks on the surface of notch bottom and at the cross section of cut specimens were observed by an optical microscope.

3. Results and Discussion

3.1 Microstructural evaluation

The typical microstructures for A4 and AC4B alloys after peak aging are shown in Fig. 2. The average cooling rate near the liquids temperature was 25.6 K/s for both specimens, and the secondary dendrite arm spacing of the primary α phase was 15.6 μm . The eutectic Si phase shows a spherical form after the modification by Sr and solution treatment among the α phase. In the AC4B alloy, besides the Si phase, Fe-compound ($\alpha\text{-Al}_{15}(\text{Fe}, \text{Mn})_3\text{Si}_2$) crystallizes into dendritic patterns, along with small quantities of particulate or needle-like Fe-compound ($\beta\text{-Al}_5\text{FeSi}$). Further, some defects such as micro-porosities or micro-shrinkages appear in both alloys as shown in Fig. 3. The average and the maximum diameters measured at 14.9 μm and 101 μm , respectively.

3.2 Influence of notch size on fatigue strength

The results of fatigue tests on specimens with $\rho = 2$ mm are shown in Fig. 4. The arrows in the figure indicate that specimen wasn't broken even after 10^7 time cycles. For both A4 and AC4B alloys, no breakdowns occur even at a stress of 105 MPa. However, at 110 MPa, all A4 alloy specimens fail prior to 10^7 repetitions; as well some AC4B alloy specimens

Fig. 4 Relationship between applied stress and number of cycle at the rotating bending fatigue test ($\rho = 2$ mm). Arrows show that specimen wasn't broken during 10^7 cycles, so experiments stopped.

Fig. 5 Non-propagating cracks on the surface of a notch bottom of an AC4B alloy ($\rho = 2$ mm, $\sigma = 105$ MPa) specimen.

break down by 10^7 cycles. These test results appear to indicate no clear difference of fatigue characteristics between A4 alloy and AC4B alloys. Figure 5 shows fine non-propagating cracks observed at the notch bottom in an AC4B alloy specimen tested at 105 MPa. Micro-cracks are generated from casting defects, and in this case the maximum length of the cracks measures about 40 μm . Similar results are observed for both AC4B and A4 alloy specimens tested at 100 to 105 MPa.

It is generally recognized that experimental results of notch free specimens are significantly scattered in fatigue tests, since there are differences in stress distribution and concentration in specimens even at the same nominal stresses, due to different internal cast defects, sizes, shapes and positions. Therefore, different behaviors of crack initiation, crack arrest and growth occur in every specimens.¹⁰⁻¹³ If numbers of tests are carried out, the variations in test results may increase with increasing variation of the casting defects at 110 MPa in Fig. 4, as much as that with smooth materials. Therefore, fatigue limit stress can be concluded to 105 MPa at $\rho = 2$ mm. Murakami proposes the two kind of limit stress in the relationship between the fatigue strength, σ_w and the stress concentration factor, Kt in notched specimen;¹⁵ one is the crack generation stress, σ_{w1} , where cracks initiate, and the other is the fatigue limit stress, σ_{w2} , where cracks start to propagate, connect each other and cause the failure. So, at the condition below σ_{w1} , no cracks are

Table 2 Relationship between the notch radius and the stress concentration factor.

ρ (mm)	K_t
2.0	1.33
1.0	1.58
0.3	2.36
0.1	3.78

introduced, and between σ_{w1} and σ_{w2} , specimens can survive against rotating bending stress even though large-scale non-propagating cracks are observed around the entire circumference specimen. In generally, σ_{w1} and σ_{w2} are almost identical in smooth specimens, since fine cracks generated from casting defects grow rapidly and break the specimen. However, the two different values appear in notched specimen, and the radius, ρ_0 is defined as the minimum notch radius where σ_{w2} appears. Since the notch depth h is fixed at 0.5 mm, the stress concentration factor, K_t increases with decreasing notch radius, ρ as shown in Table 2.¹⁴⁾ Large non-propagating cracks were never observed in the $\rho = 2$ mm specimens, so it can be said that ρ_0 is less than 2 mm. Therefore crack generation and fatigue strength are governed by casting defects when ρ is larger than ρ_0 , as well as in notch free specimens.

The results for specimens of $\rho = 1$ mm are presented in Fig. 6. A4 alloys have a higher fatigue strength; perhaps because the structure of an A4 alloy specimen reveals almost no casting defects in the notch bottoms of the $\sigma = 100$ and 105 MPa test specimens; whereas large casting defects were present in the notch bottoms of the two AC4B specimens tested at $\sigma = 100$ MPa. However non-propagating cracks are observed at the notch bottom of both A4 and AC4B specimens. This type of short non-propagating crack is generated from casting defects; but some cracks are generated without casting defects as shown in Fig. 7. This is because the stress concentration factor at the bottom of a crack is higher than that of the $\rho = 2$ mm specimens; so eutectic Si and Fe compounds serve as sites of crack generation. Contrarily, the probability of cracks from casting defects can be reduced. In addition, since the short non-propagating cracks appear, the minimum notch radius may be around 1 mm in both A4 and AC4B specimens.

At $\rho = 0.3$ mm, the AC4B alloy exhibited higher fatigue

Fig. 10 Relationship between applied stress and number of cycle at the rotating bending fatigue test ($\rho = 0.1$ mm).

in crack number along with an increase in stress, and specimens are broken before 10^7 cycles at $\sigma = 95$ MPa; whereas breakdown did not occur for the AC4B alloy even at $\sigma = 95$ MPa although large non-propagating cracks were present in over 70% of the circumference on the notch bottom. Moreover, even though large casting defects are present at the notch bottom as indicated in Fig. 9(b), crack propagation is arrested. Consequently, with smooth and large notched materials, large casting defects act as crack generation sites; thus causing large variations in fatigue strength. But with notches smaller than ρ_0 , the propagation subsequent to crack generation governs fatigue strength, and casting defects are not a determining factor for fatigue strength.

Figure 10 shows the results of 0.1 mm notched specimens. The A4 alloy broke down prior to 10^6 cycles at a stress of $\sigma = 90$ MPa, whereas some specimens survive after 10^7 cycles at $\sigma = 85$ MPa. Contrarily, the AC4B alloy exhibited markedly higher fatigue strength than the A4; no AC4B alloy broke down even at 90 MPa, although large cracks were observed over the entire circumference of the specimen. Thus 90 MPa could be close to the fatigue limit stress, σ_{w2} of the AC4B alloy. However, large non-propagating cracks are presented in both of A4 and AC4B alloy at this sharpest notch bottom and extended for nearly the entire circumference. To clarify the differences between A4 and AC4B alloys in crack generation and propagation, surface and transverse cross sections of the tested specimens were examined. Figures 11(a) and (b) show the generated non-propagating cracks on the surface of A4 alloy. The cracks extend linearly along the notch. However, non-propagating cracks grow through the interfaces between eutectic Si or Fe-compounds and the α -phase in a zigzag shape in regions where eutectic Si or Fe-compounds are crystallized of AC4B alloys as shown in Figs. 11(c) and (d). Moreover, large numbers of cracks are generated from Fe-compounds at the individual direction as shown in Figs. 12(b)–(d) in comparison with cracks of A4 alloy (Fig. 12(a)). So the stress concentration around each crack tips may be reduced. In addition, crack propagation stopped on Fe-compounds in a few cases; indicating that Fe-compounds may also directly interrupt crack propagation. Eutectic including Fe-compounds, therefore, is one of the reasons to increasing the plastic deformation resistance against crack propagation due to the extended crack length

Fig. 11 Difference of growth direction of non-propagating cracks of AC4B alloy ($\rho = 0.1$ mm, $\sigma = 75$ MPa) specimen, microcracks growing along the Si particles (a, b), and between the Fe-compounds (c, d).

Fig. 12 Non-propagating cracks of Al-Si-Cu-Mg (A4) alloy ($\rho = 0.1$ mm, $\sigma = 85$ MPa), (a) and AC4B alloy ($\rho = 0.1$ mm, $\sigma = 90$ MPa) (b)–(d) specimens through the cross sections.

and the number, and the changed crack growth direction. However the more detailed micro-scopic fracture examination is necessary to conclude the influence of Fe-compound.

3.3 Evaluation of Fe-bearing alloy based on fatigue limiting stress

Figure 13 shows the relationship between fatigue limit stress, σ_w and the stress concentration factor, Kt . The stress σ_w is determined as 5 MPa below the minimum stress where

Fig. 13 Relationship between stress concentration factor and the fatigue limit stress.

breakdown occurred prior to 10^7 cycles. That would mean that the materials could withstand these stresses up to the 10^7 cycles. The σ_{w1} value, which is the stress of the crack generation, of the AC4B alloy is lower than that of the A4 as shown in Fig. 13. So, the Fe-compound could initiate the fatigue crack. In the meantime, for the AC4B alloy, the fatigue limit stress is unchanged with notch sizes sharper than $\rho = 1$ mm, and σ_{w2} are estimated to be 90–95 MPa. For the A4 alloys, the fatigue limit stress decreases continuously from 100 to 80 MPa with increasing Kt from 1.6 to 3.8. From the above results, it is concluded that the fatigue strength for the AC4B alloy is higher than for the high-purity A4 alloy under conditions of a high stress concentration factor; and that Fe-compounds thus have a positive effect on fatigue strength. There is the possibility that the impurities such as Fe element become higher in an alloy if recycled materials are positively intermixed for purposes of the environmental protection. Figure 13 shows one of the advantages on the fatigue characteristics of the high-impurities alloy, where eutectic structure or intermetallic compound is distributed.

4. Conclusions

Rotating bending fatigue tests were carried out for heat treated JIS-AC4B and high-purity alloys containing similar

amounts of Si, Cu and Mg in order to evaluate any influences of the solidification microstructure, defects and the stress concentration factor on fatigue characteristics. The results obtained are summarized as follows.

(1) Microstructures of specimens consist of dendritic α phase, rounded eutectic Si, Al_2Cu and Mg_2Si phases in both alloys. Fe compounds appear among the dendrites only in the AC4B alloy. Micro-porosity and shrinkage appear in every specimen.

(2) When the alloys have notches of 1 mm radius or greater, both AC4B and iron free AC4B type alloys show the same fatigue sequence; that indicates that the fatigue strength was determined by the gas and shrinkage porosities and the initial cracking process.

(3) In alloys that have sharp notches of 0.3 mm radius or smaller and in which the stress concentration factor is higher, cracks originate and propagate not from micro-porosity, which have almost no influence on the fatigue process, but also from the notch bottom.

(4) When the stress concentration factor was higher, the fatigue strength of the AC4B alloy, which contains Fe-compounds, was higher than that of the compound free A4 alloy. Fe-compounds, is perhaps one of the reasons to increasing the plastic deformation resistance against crack propagation due to the extended the crack length and number, and the changed crack growth direction.

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