General paper

FATIGUE CRACK INITIATION AND GROWTH MECHANISMS IN PARTICLE-REINFORCED ALUMINUM MATRIX COMPOSITES

Masahiro JONO and Atsushi SUGETA

*Department of Mechanical Engineering, Osaka Univ.,
2-1, Yamada-oka, Suita, Osaka, 565 Japan*

Abstract: Reversed plane bending fatigue tests were carried out on three kinds of particle-reinforced aluminum matrix composites, Si/A2024, SiC/A2024 and SiC/AC4CH. SiC/A2024 and two kinds of Si/A2024 which have different size and distribution of Si particles were consolidated by Powder Metallurgy(PM) process, and SiC/AC4CH was made by casting process. The initiation and growth behavior of small surface cracks was continuously monitored by the replication technique and investigated in detail. It was found that both fatigue crack initiation strength and crack growth resistance became higher in the order, SiC/AC4CH, Si/A2024 with coarse Si particle, Si/A2024 with fine Si particle, SiC/A2024. When stress amplitude was normalized by tensile strength, the difference in the fatigue strength of P/M composites was scarcely observed, but the casting composite exhibited lower strength than P/M one.

Key words: *Fatigue, Metal Matrix Composite, Crack Initiation, Small Crack Growth, Particle-Reinforcement*

1 INTRODUCTION

Metal matrix composites (MMCs) are promising materials for structural application in severe conditions. SiC- or Al_2O_3 -based fibers, whiskers, or particles as well as carbon fibers are used to reinforce aluminum, magnesium, or titanium matrix alloys. Particle reinforced composites are useful because the anisotropy of static and the fatigue strength is smaller than that in fiber reinforced composites. It is widely understood that particle reinforced MMC have high stiffness and strength as well as high wear resistance compared to conventional matrix materials. However, they usually show relatively poor properties in ductility and fracture toughness, and it becomes important to clarify the fatigue properties as well as the fracture toughness to utilize the material in service. A large number of studies have been conducted on the fatigue strength and the growth behavior of long fatigue cracks of MMCs and have been demonstrated that the threshold level and the fatigue crack growth resistance is increased by reinforcing aluminum matrix with SiC particles[1-9]. However, in particle reinforced composites, it was reported that most of the fatigue life was consumed in the crack initiation stage[10]. This fact implies that the crack initiation and the small crack growth behavior are more important to utilize the material in service. There are few reports on detailed observations of fatigue crack initiation mechanisms and small surface crack growth behavior.

The objective of the present study is to investigate the effects of particle and manufacturing method on fatigue strength and small fatigue crack growth behavior. Reversed plane bending fatigue tests were carried out on SiC or Si particle-reinforced aluminum matrix composites which were made by a powder metallurgy process or casting, and the fatigue crack initiation and the small crack growth behavior were examined in detail.

2 MATERIALS AND EXPERIMENTAL PROCEDURE

Four kinds of particle-reinforced aluminum matrix composites, Si/A2024(Fine), Si/A2024(Coarse), SiC/A2024 and SiC/AC4CH were investigated. The microstructures of materials used are illustrated in Fig. 1. The Si/A2024 alloys were consolidated by a powder forging process using air atomized rapidly solidified powders with solidification rate of $10^2 - 10^3$ °C/s. The Si/A2024 (Coarse) has a some extent of powder with relatively slow solidification rate of 10^2 °C/s and shows a dispersed distribution of coarse primary Si particles(around 20 μ m), while the Si/A2024(Fine), made of fine powders with solidification rate of 10^3 °C/s (-100 mesh), has fine primary Si particles (less than 10 μ m) and uniformly distribution. Both materials have the same chemical composition and contain 25 wt.% Si as shown in Table 1. The SiC/A2024 composite was reinforced by a nominal 20 vol.% of silicon carbide particle. The composite alloy was fabricated by blending prealloyed atomized aluminum-alloy powders with SiC particles, vacuum degassing, hot pressing and finally extruding at an extrusion ratio of 21:1 into 15 mm-diameter rod. A SiC particle size varied between 2 and 10 μ m. SiC particles distributed uniformly, although the layered structure parallel to extrusion direction was observed. Al-Si matrix alloy, JIS AC4CH, was reinforced with 20%SiC particles and was made by a squeeze casting process. Casting defects at matrix/particle interfaces were observed in SEM photograph(right hand side of Fig. 1(d)). Table 2 shows the mechanical properties of materials. Si particles reinforced composites show little plastic deformation and behave in brittle manner. SiC particles reinforced P/M composite has the highest tensile strength.

Fully reversed fatigue tests under constant amplitude loading were carried out using an electro-magnetic type

(a) Si/A2024(Coarse Si particle)

(b) Si/A2024(Fine Si particle)

(c) SiC/A2024

(d) Casting SiC/AC4CH

Fig.1. Microstructure of materials investigated.

bending machine at a frequency of 30 Hz. A fatigue test specimen is shown in Fig. 2. A shallow notch, the stress concentration factor of which was 1.8, was machined in the center of in-plane bending specimen so as to localize a crack initiation within a small area. The measurement of crack length and number of cracks were made by means of plastic replicas taken from the shallow notch area at the proper intervals during fatigue tests.

3 EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Fatigue Strength

Figure 3 shows relationship between stress amplitude and number of stress cycles to crack initiation, N_i , and that to failure, N_f . The stress amplitude indicated in the left hand ordinate means the local one at the shallow notch root, which is calculated by multiplying the stress concentration factor to the nominal stress. The crack initiation life, N_i is defined as the number of stress cycles at crack length of 0.2 mm. The P/M composite reinforced by SiC particles, SiC/A2024, which has the highest tensile strength, exhibits the superior fatigue strength. In the Si/A2024 with coarse Si particles, the dependence of the fatigue strength on the specimen orientations was examined and the fatigue life becomes longer in the order, L-C, C-L, C-C orientation. On the other hand, in the Si/A2024 with fine and homogeneous distribution Si particle, Si/A2024(Fine), little difference in fatigue strength for the specimen orientation was observed[11]. By comparing the test results of fine and coarse Si particle reinforced composites it can be said that fine and uniform distribution of primary Si particles increases the fatigue crack initiation strength. In the casting composite, SiC/AC4CH, fatigue cracks initiated about at 10^4 cycles irrespective of the stress level. It was found that N_i was relatively short comparing with the P/M composites and the most of the fatigue life was consumed in the small crack propagation stage. And also, the fatigue strength is lowest in the materials investigated.

Figure 4(a) shows SEM photograph of crack initiation site of the SiC/2024 P/M composite and the arrows in photograph indicate the fatigue crack origins. In this case, cracks initiated and coalesced. SiC particles were

Table 1. Chemical composition of the Si particle reinforced composite used.(wt.%)

Si	Cu	Mg	Mn	Fe	Zn	Al
24.51	3.33	0.40	0.44	0.40	0.01	bal

Table 2. Mechanical properties of the materials used.

Materials and matrixes	0.2% proof stress $\sigma_{0.2}$ (MPa)	Tensile strength σ_B (MPa)	Elongation δ (%)	E (GPa)
Si/A2024(Fine)	—	485	—	92
Si/A2024(Coarse)	—	410	—	92
SiC/A2024	462	594	5.9	110
SiC/AC4CH	331	352	0.4	96
A2024-T6(Ingot metallurgy)	403	476	8.5	71
AC4CH-T6	220	276	6.0	55

Fig.2. Test specimen configuration.

Fig.3. S-N curves.

observed in the crack initiation site. The ultimate analysis of the crack initiation site was made by using EDX(Energy Dispersive X-ray analyser) and the results are shown in Fig. 4(b). Although Al, Si and Cu elements were detected, the intensity of Si element was smaller than that of Al element. This implies that debonding of a matrix/particle interface and fracture of SiC particle hardly occur in the crack initiation site. Therefore, it was thought that a fatigue crack initiated in matrix in the vicinity of SiC particles by cyclic slip deformation.

Figure 5 shows optical photographs of specimen surface after crack initiation in the Si particle reinforced composites. In both composites, a fatigue crack initiated in the vicinity of the primary Si particle/matrix interface. Since a large primary defect was not observed in crack origin, it was thought that a crack initiated by the slip deformation or the interface debonding under cyclic loading. In the Si/A2024 with coarse Si particles, the relatively large sized Si particles were distributed dispersely and fatigue crack almost initiated at that. Therefore it was thought that the fatigue strength should depend on size and shape of Si particle at which crack initiated. Since large or middle sized Si particles were slightly deformed during the forging stage, the shape of projected area of those particles to the perpendicular to the loading axis varied with

(a) SEM photograph of crack initiation site.

 (b) Ultimate analysis of crack origin.
 Fig.4. Observation of crack initiation site of SiC/A2024.

(a) Si/A2024(Coarse)

(b) Si/A2024(Fine)

Fig.5. Photographs of specimen surface after the crack initiation in Si particle reinforced composites.

specimen orientation. It was reported in the previous papers[11,12] that the difference of the fatigue strength for the different specimen orientation as mentioned above could be well explained considering this shape change of Si particle. On the other hand, in the Si/A2024 with fine and homogeneous distribution Si particles, since fine primary Si particles were hardly deformed during the forging stage, the dependence of the fatigue strength on the specimen orientation was scarcely observed.

Figure 6 shows micrographs of the crack initiation site of the SiC/AC4CH casting composite and an arrow in photograph indicates the fatigue crack origin. A fatigue crack initiated from the casting defect at the matrix/particle interface, irrespective of stress level. Therefore, fatigue crack initiated easily as compared to P/M MMCs and this premature crack initiation was thought to result in the

Fig.6. Photograph of crack initiation site in casting SiC particle reinforced composite.

Fig.7. $\sigma_a/\sigma_B - N$ curve.

lowest fatigue crack initiation strength.

As above mentioned, the fatigue crack initiation strength became higher in the order, SiC/AC4CH, Si/A2024 with coarse Si particles, Si/A2024 with fine Si particles, SiC/A2024, corresponding to the order of tensile strength of these materials. The relationship between stress amplitude normalized by tensile strength and fatigue life is shown in Fig. 7. The difference in the fatigue strength of P/M metal matrix composites was scarcely observed and it was found that the reinforcement using SiC or Si particles improved both the tensile strength and the fatigue strength. The ratio of the fatigue strength at 10^7 cycles to the tensile strength is almost equal to 0.65 and is higher than that in conventional metals. In the case that a fatigue crack initiated at inclusion or defect, it is well known that a fatigue strength depend strongly on the effective volume which is subjected to higher stress. Therefore, it was thought that the high ratio was caused by the small effective volume of this specimen due to the shallow notch.

3.2 Fatigue Crack Growth Behavior

Optical micrographs of fatigue crack path of Si particle reinforced composites are shown in Fig. 8. A fatigue crack

initiated in the vicinity of the primary Si particle/matrix interface and grew in the aluminum matrix. When the fatigue crack reached to Si particles, the crack deflected along the small or middle sized Si particles while it passed through some relatively large Si particles. Therefore, the fatigue crack was found to grow in a zig-zag manner microscopically, although the crack propagated straight in the direction normal to the loading axis macroscopically. In the composites with fine Si particles, Si/A2024(Fine), the crack seldom passed through the Si particles and a large number of smaller crack deflection was observed.

Figure 9 shows macroscopic crack growth rate, da/dn , as a function of a maximum stress intensity factor, K_{max} . K_{max} was calculated by Newman-Raju equation[13] using the average aspect ratio of the semi-elliptical surface crack measured by means of a beach marking method. Since it

Fig.8. Optical micrograph of crack path in Si/A2024.

Fig.9. Relationship between crack growth rate, da/dn , and maximum stress intensity factor, K_{max} in Si/A2024.

Fig.10. Example of fatigue crack growth behavior in SiC particle reinforced P/M composite, SiC/A2024.

was recognized that a small fatigue crack fully open under tensile loading, K_{max} was thought to nearly equal to ΔK_{eff} . Although there found a fairly large scatter, da/dn can be expressed by Paris equation in terms of K_{max} for each composites irrespective of stress levels and specimen orientations. Fatigue crack growth rate was found faster in the composite with the coarse Si particles (Si/A2024 (Coarse)) than in the composite with the fine Si particle (Si/A2024 (Fine)). It was concluded that more deflective behavior of crack growth in Si/A2024 (Fine) resulted in the increase of the intrinsic crack growth resistance due to a longer crack path and more reduction in driving force for crack growth.

SEM micrographs illustrated in Fig. 10 show an example of fatigue crack growth behavior in SiC particle reinforced P/M composite. A fatigue crack initiated in matrix in the vicinity of SiC particle and grew in the aluminum matrix. When the main crack reached to SiC particle, the main crack arrested and micro subcrack initiated at SiC particles near the main crack tip. The

micro subcrack grew straight in the direction normal to the loading axis macroscopically during the following load cycles and the main crack joined with the micro subcrack. Since microcrack initiation and crack coalescence were frequently observed, it was found that this is main mechanism of fatigue crack growth in SiC particle reinforced P/M composite. The crack coalescence formed the crack bridging and resulted in the more deflected crack path as shown in Fig.10.

Figure 11 shows relationship between da/dn and K_{max} in the SiC/A2024 P/M composite and the SiC/AC4CH casting composite. In this figure, the solid and dashed lines indicate $da/dn - K_{max}$ relationships in the Si/A2024 (Coarse) and the Si/A2024 (Fine) shown in Fig. 9, respectively. In the SiC/A2024, although there is a fairly large scatter, da/dn can be expressed by Paris equation irrespective of stress levels. Comparing to the Si particle reinforced composites, the SiC/A2024 composite exhibits the superior fatigue crack growth resistance due to a crack bridging effect and a longer crack path.

Fig.11. $da/dn - K_{max}$ relationship.

Figure 12 shows optical micrograph of fatigue crack path of the SiC reinforced casting composite, SiC/AC4CH. A fatigue crack initiated at a casting defect and grew in the direction inclined almost 50° against the loading axis in the early stage and then propagated in the direction normal to it. The crack length which the crack grew slantingly is found to longer as the stress level become lower while the crack inclination angle is almost 50° irrespective of stress levels. A fatigue crack grew continuously in aluminum matrix and, crack arrest or micro subcrack initiation, which was frequently observed in SiC particle reinforced P/M composites, was hardly observed. In the casting composite, since the interface between the matrix and SiC particle is weak due to casting defects at interfaces shown in Fig.1,

Fig.12. Optical micrograph of fatigue crack path of SiC reinforced casting composite, SiC/AC4CH.

SiC particles caused the fatigue crack deflection but could not arrest it. The crack growth rates of SiC/AC4CH were shown in Fig. 11 by triangle symbols. Fatigue crack growth rates decreased with crack growth after the crack initiation, and then gradually increased. It was thought that this decrease resulted from the mismatching of the fracture surfaces caused by the crack deviation in the early stage. The crack initiation threshold stress intensity factor, K_I , was almost equal to $4 \text{ MPa}\sqrt{\text{m}}$ in the P/M composites. In the casting composite, a fatigue crack could initiate and grow at K_{max} below this threshold, and the lowest fatigue crack resistance was observed.

4 CONCLUSIONS

Reversed plane bending fatigue tests were carried out on four kinds of particle-reinforced aluminum matrix composites. i.e. SiC particle reinforced P/M composite, SiC/A2024, SiC particle reinforced casting composite, SiC/AC4CH and two kind of Si particle reinforced composite, Si/A2024(Fine) and Si/A2024(Coarse). The effects of particles and manufacturing method on fatigue strength were examined. The results obtained can be summarized as follows;

1) It was found that the fatigue crack initiation strength became higher in the order, SiC/AC4CH casting composite, Si/A2024 with coarse Si particles, Si/A2024 with fine Si particles, SiC/A2024 P/M composite corresponding to the order of tensile strength. When the stress amplitudes were normalized by tensile strength, the difference in the fatigue strength of P/M metal matrix composites was scarcely observed, but the casting composite exhibited lower strength than P/M one.

2) In P/M composites, a fatigue crack initiated in matrix in the vicinity of SiC or Si reinforcement particle. On the other hands, in the SiC/AC4CH, which has casting defects at particle/matrix interfaces, a fatigue crack easily initiated at a casting defect and this premature crack initiation was found to result in the lowest fatigue crack initiation strength.

3) A fatigue crack deflected along SiC or Si reinforcement particles and grew in a zig-zag manner microscopically, although the crack propagated straight in the direction normal to the loading axis macroscopically except for the early stage of the casting composite. In the

SiC reinforced P/M composite, a micro subcrack frequently initiated in the front of main crack and coalesced. This crack coalescence mechanism resulted in more deflective crack path, which was thought to result in reducing growth rates due to the bridging effect.

4) The fatigue crack resistance became higher in the order, Si/A2024 with coarse Si, Si/A2024 with fine Si, SiC/A2024. It was concluded that more deflective behavior of crack growth resulted in increase of the intrinsic crack growth resistance due to a longer crack path and more reduction in driving force for crack growth. In casting composites, fatigue crack could grow at the stress intensity factor below the threshold level of P/M composites and the lowest fatigue crack resistance was observed.

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