Fatigue Fracture Behavior of SiC Whisker/Aluminum Matrix Composite under In-Phase and Out-of-Phase Tension/Torsion Loading*

Kohji MINOSHIMA**, Shigeyoshi SATOH***
and Kenjiro KOMAI**

We describe an investigation on the fatigue fracture behavior of an SiC whisker reinforced A6061 aluminum alloy fabricated by a squeeze casting process under combined tension/torsion loading at room temperature. Attention was focused on in-phase and out-of-phase tension/torsion loading. The tests were conducted under a load-controlled condition keeping a constant value of the combined stress ratio, $\alpha = \tau_{\max}/\sigma_{\max}$. Irrespective of loading condition, the mechanical properties of the composite including fatigue strength were superior to those of an unreinforced A6061 alloy, not only under uniaxial loading, but also under combined in-phase and out-of-phase tension/torsion loading. In the case of the unreinforced matrix material, the fatigue strength under out-of-phase combined loading was smaller than that under in-phase loading. However, for the composite, the fatigue strength under out-of-phase combined loading was higher than that under in-phase combined loading. The crack initiation and propagation behavior was closely examined using a surface replication technique, and the fracture mechanisms under in-phase and out-of-phase combined loading were discussed.

Key Words: Composite Material, Metal Matrix Composite, Fracture, Fatigue, Combined Stress, Tension/Torsion Loading, In-Phase Loading, Out-of-Phase Loading, Crack Initiation, Whisker, Aluminum Matrix Composite

1. Introduction

Continuous progress in science and technology creates increasing demand for further improved structural materials; the mechanical properties required in many technological fields are high-strength, low-specific density, high wear resistance, and heat-resistant property. Of various structural materials, metal matrix composites have attracted engineers and researchers because of their potentials to meet such demands. Especially short fiber such as whisker reinforced metals have better machinability compared with long fiber reinforced metals, and are easy of secondary machining such as extrusion. Many researches have been performed on strengthening

mechanisms⁽¹⁾, fracture and fatigue⁽²⁾⁻⁽⁶⁾ behavior, and environmental influences on fracture⁽⁴⁾ and corrosion behavior⁽⁷⁾. However, fracture behavior under combined loading is scarcely reported⁽⁵⁾, although it is important from the standpoints of the application of a composite to machines and structures.

The authors⁽⁵⁾ have already conducted quasi-static and fatigue tests in an SiC whisker reinforced aluminum alloy under in-phase tension/torsion combined loading at room and elevated temperatures: we reported that the whisker reinforcement effectively strengthened both of the quasi-static and fatigue strengths of the composite not only under uniaxial tensile loading but also under in-phase tension/torsion combined loading. We also discussed an influence of multiaxial loading and temperature on the fracture mechanisms. In this investigation, we have conducted quasi-static and fatigue tests of an SiC whisker reinforced aluminum alloy (SiC_w/A6061-T6) and its unreinforced metals (A6061-T6) under out-of-phase combined tension/torsion loading at room temperature at a various combined stress ratio $\alpha (= \tau_{\max}/\sigma_{\max})$,

* Received 9th October, 1977. Japanese original: Trans. Jpn. Soc. Mech. Eng., Vol. 62, No. 601, A (1996), p. 2001-2007 (Received 25th December, 1995)

** Department of Mechanical Engineering, Graduate School of Engineering, Kyoto University, Yoshida-Honmachi, Sakyo-Ku, Kyoto 606-8501, Japan

*** JR West Company, Ltd., Osaka, Japan

where the ratio of axial stress to torsional stress does not keep constant, and the direction of a principal stress rotates during a fatigue cycle. Crack initiation and propagation were closely examined by using a replication technique, and an influence of out-of-phase combined loading on the fracture behavior of the composite and its unreinforced matrix material is discussed.

2. Experimental Procedures

The material tested was an SiC whisker reinforced A6061 aluminum alloy ($V_f=17\%$) and its unreinforced matrix material, A6061. The composite was fabricated through a squeeze casting process. Table 1 summarizes the chemical composition of the matrix material. Both of the materials were extruded to a final extrusion ratio of 28, and thus most whisker aligned in the longitudinal direction, although some whisker rich or matrix rich areas existed microscopically. The average diameter of the whisker was $0.84\text{ }\mu\text{m}$, and the average length after processing was $4.86\text{ }\mu\text{m}$. The composite and the matrix material were heat treated to a T6 condition: the materials were solution heat treated at 530°C for 2h, then water quenched, and were aged at 175°C for 8h, followed by air cooling. Extruded materials of 18.9 mm in diameter were machined into a smooth round specimen shown in Fig. 1 in the longitudinal direction, i.e., extruding direction. The specimen surface was polished with emery papers (#1500) followed with final finish with a diamond paste.

The testing machine employed was a computer-controlled electro-hydraulic tension-torsion fatigue testing machine (load capacity: $\pm 100\text{ kN}$, $\pm 1\text{ kN}\cdot\text{m}$). Static and fatigue tests under combined loading were conducted in laboratory air at room temperature. Static tests were conducted under a load-controlled condition keeping a constant value of a combined stress ratio, $\alpha=\tau/\sigma$, where σ is the axial stress and τ

Table 1 Chemical composition of A6061 Al alloy, wt%

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
0.54	0.23	0.24	0.02	1.00	0.19	0.01	0.02	R

Fig. 1 Shape and dimensions of test specimens. All dimensions are in mm

the torsional stress. The combined stress ratio was varied at four different values between zero (pure tension) and the infinity (pure torsion). The loading rate of a faster rate of the two was selected at 0.8 MPa/s .

Fatigue tests at a stress ratio $R (= \sigma_{\min}/\sigma_{\max} = \tau_{\min}/\tau_{\max})$ of 0.1 were performed at a stress cycle frequency of 5 Hz under in-phase (phase angle between tension and torsion loading, ϕ , of 0°) and out-of-phase ($\phi=180^\circ$) combined tension/torsion loading. In-phase fatigue tests were conducted under a load-controlled condition keeping a combined stress ratio, $\alpha=\tau/\sigma$ of a sample surface constant. In the case of out-of-phase loading, however, the combined stress ratio varies during a fatigue cycle, unlike in-phase fatigue loading, and therefore, the combined stress ratio $\alpha=\tau_{\max}/\sigma_{\max}$, was kept constant, where $\sigma_{\max}$ is the maximum axial stress and $\tau_{\max}$ the maximum torsional stress in a single fatigue cycle. Some fatigue tests were periodically interrupted, and crack initiation and growth behaviors were closely examined by using a surface replication technique. Fatigued specimen surfaces and fracture surfaces were closely examined with a scanning electron microscope (SEM: JSM-5400-LV by JEOL).

3. Experimental Results and Discussions

3.1 Quasi-static fracture behavior

Figure 2 shows the static strengths under in-phase combined loading, which are plotted in relation of axial stress and torsional stress. The arrows in the figure indicate that specimens did not completely fracture even though the maximum torsional angle (about ± 50 degrees) was applied to the specimens. The solid lines shown in the figure are the predicted failure strengths based on the Tsai-Hill failure

Fig. 2 Quasi-static strength under in-phase tension/torsion combined loading

criterion⁽⁸⁾. The elongation at break under uniaxial tension was 11% for the composite and was 33% for the matrix material. The static strengths of the composite and unreinforced matrix material agreed well with the Tsai-Hill failure criterion. The second point we must note is that the static strength of the composite was higher than that of an unreinforced A6061 alloy, not only under uniaxial loading, but also under combined tension/torsion loading⁽⁶⁾. This indicates that whisker reinforcement effectively increases the quasi-static composite strength under combined loading, that is very important from a technological standpoint.

3.2 Fatigue fracture behavior

Figures 3(a) and (b) respectively show $S-N$ curves under uniaxial and torsional loading. The fatigue strength of the composite under both loading conditions was higher than those of unreinforced matrix material, and it is clear that whisker reinforcements are very effective to increase the fatigue strength of the composite.

Fig. 3(a) $S-N$ curves under uniaxial loading

Fig. 3(b) $S-N$ curves under torsional loading

Figure 4 shows $S-N$ curves under in-phase and out-of-phase combined tension/torsion loading at a combined stress ratio α of 0.5, 1 and 2. The ordinate adopted in these figures is maximum axial stress. From these figures, it is clear that the fatigue strength

(a) $\alpha=0.5$

(b) $\alpha=1$

(c) $\alpha=2$

Fig. 4 $S-N$ curves under in-phase and out-of-phase tension/torsion combined loading

of the composite was higher than that of the matrix material under in-phase and out-of-phase loading. As for matrix material, the fatigue strength under out-of-phase combined loading was lower than that under in-phase combined loading, irrespective of α value. However, for the composite, the fatigue strength under out-of-phase loading was superior to those under in-phase loading. This means that the strengthening effect by whisker reinforcement is more effective under out-of-phase loading than under in-phase loading. The fatigue strength of unreinforced metals was reported lower under out-of-phase loading^{(9),(10)}, and this is consistent with the results obtained in the matrix material. However, we must note that the effect of out-of-phase loading on the composite was contrary to that of the unreinforced

(a) In-phase loading

(b) Out-of-phase loading

Fig. 5 Macroscopic fracture morphology of A6061 Al alloy ($\alpha=2$)

(a) In-phase loading

(b) Out-of-phase loading

Fig. 6 Macroscopic fracture morphology of SiCw/A6061 ($\alpha=0.5$)

matrix material.

3.3 Macroscopic fracture morphology

Figures 5 and 6 show macroscopic fracture morphology of the matrix and the composite materials. The solid lines shown in the figures are the planes where a shear stress range $\Delta\tau_\theta$ takes the maximum. As was previously reported⁽⁵⁾, final failure of both of the composite and the matrix material was brought about by a crack that was in a plane where a shear stress range $\Delta\tau_\theta$ took the maximum, or the maximum shear stress range plane. We must note that there are two planes where the shear stress range takes the maximum: of these two planes, the final failure was resulted from a crack in a plane that was near the longitudinal, or axial direction, except for matrix material under out-of-phase loading. In the case of matrix material under out-of-phase loading, the final failure was brought about by a crack in a maximum shear stress plane near the transverse direction.

3.4 Crack initiation and growth behavior

As was discussed, the influence of out-of-phase tension/torsion loading on fatigue strength and macroscopic fracture morphology of the composite is different from that of the matrix material. In order to investigate the fracture mechanisms, crack initiation and propagation behavior was closely examined by a replication technique, selecting the loading condition of $\alpha=1$, where the largest difference of the fatigue strength between the composite and the matrix material was observed. The surface replication was made by three replicas, and thereby replication in an entire parallel part of a specimen could be done. A crack length and crack orientation was defined as is shown in Fig. 7: a crack length was measured between both ends of a crack; crack orientation was defined as an angle between the line connecting both ends of a crack and an axial, or longitudinal direction.

3.4.1 Crack initiation orientation The results of crack initiation orientation are summarized in Figs. 8 (matrix material) and 9 (composite). The crack orientation angle was plotted for a crack whose

Fig. 7 Definition of crack length and crack orientation

(a) In-phase combined loading

(b) Out-of-phase combined loading

Fig. 8 Crack initiation orientation of A6061 Al alloy ($\alpha=1$)

initiation was first confirmed. The crack length plotted ranged from 0.01 mm to 0.89 mm, and the average was 0.16 mm. From these figures, it is clear that almost all the cracks of both materials were initiated in the neighborhood of a plane where $\Delta\tau_\theta$ took the maximum. For the matrix material, most of the cracks under in-phase tension/torsion loading were in the maximum $\Delta\tau_\theta$ plane which was near the longitudinal direction (L-type crack), whereas under out-of-phase loading, most of the cracks were in the maximum $\Delta\tau_\theta$ plane near the transverse direction (T-type crack). As for the composite under in-phase tension/torsion loading, L-type cracks were dominant. Under out-of-phase loading, both L and T-type cracks were observed. However, L-type cracks were dominant compared with T-type cracks unlike the matrix material.

3.4.2 Crack growth behavior Figures 10 and 11 respectively show changes in crack length of the

(a) In-phase combined loading

(b) Out-of-phase combined loading

Fig. 9 Crack initiation orientation of SiC_w/A6061 ($\alpha=1$)

matrix material and the composite with stress cycles. In Fig. 10, changes in L-type crack are shown for in-phase loading, whereas those in T-type crack for out-of-phase loading, both of which respectively caused the final failure. Figure 11(a) summarizes the changes in L-type crack which brought about the final failure of the composite under both in-phase and out-of-phase loading, whereas Fig. 11(b) shows changes in L and T-type cracks, which were observed under out-of-phase tension/torsion loading.

For the matrix material at a high stress level (Fig. 10(a)), there was no difference in crack growth behavior between in-phase and out-of-phase combined loading, and this agreed with no difference in fatigue life. However, at a low stress level, T-type cracks observed under out-of-phase loading were initiated earlier, and propagated faster than L-type cracks observed under in-phase loading. This well agreed with the results that fatigue strength under out-of-phase loading was lower than that under in-phase

(a) High stress level ($\sigma_{\max}=205$ MPa) (b) Low stress level ($\sigma_{\max}=182$ MPa)

Fig. 10 Crack growth curves in A6061 Al alloy under in-phase and out-of-phase combined loading

loading at low stress level. As for the composite, crack growth rate of an L-type crack, which led final failure, was faster under in-phase loading than under out-of-phase loading (see Fig. 11(a)). Under out-of-phase loading, an L-type crack initiated earlier and propagated faster than a T-type crack.

For the matrix material, a T-type crack observed under out-of-phase combined loading initiated earlier and propagated faster compared with an L-type crack observed under in-phase loading, resulting in lower fatigue strength under out-of-phase loading. When we compare the crack growth behavior between the matrix material and the composite, a noticeable difference is that a crack initiated earlier at about 10% of fatigue lives in the composite: most of fatigue lives of the composite were dominated by fatigue growth stage, and at the same time the growth rate was smaller under out-of-phase combined loading than under in-phase loading, resulting in longer

(a) Changes in L type crack under in-phase and out-of-phase loading

(b) Comparison between L type and T type crack growth behavior under out-of-phase loading

Fig. 11 Crack growth curves in SiC_w/A6061 under combined loading

fatigue life under out-of-phase loading.

3.5 Fracture surface morphology

In the case of the matrix material, striations could be observed under both in-phase and out-of-phase loading. However, a difference of fracture morphology between under uniaxial loading and tension/torsion loading was that fracture surface rubbed each other, in particular, under out-of-phase loading, and tire tracks and rub marks were observed. A crack initiation site was in a sample surface, irrespective of loading mode.

As for composite material, a crack initiated in the specimen surface. However, large inclusion or void that were observed in the SiC_w/Al composite in the crack initiation site⁽⁵⁾ could not be seen. Figure 12 shows SEM photographs of a specimen surface of a fatigued composite under out-of-phase loading at $\alpha=1$. An L-type crack initiated at whisker/matrix interface (Fig. 12(a)); a crack initiated at a whisker end

Fig. 12 Fatigued sample surface of SiC_w/A6061 under out-of-phase combined loading, imaged with SEM ($\alpha = 1$, $\sigma_{\max} = 275$ MPa)

(Fig. 12(b)), and it propagated with whisker/matrix interfacial debonding and whisker pull-out (Fig. 12(c)), and then coalesced each other, and finally it formed a T-type crack. On the fracture surface under in-phase and out-of-phase loading, whisker pull-out could be seen, and some whiskers were exposed on the fracture surface of an L-type crack. Similarly to the matrix material, wear debris existed on the fracture surface of an L-type crack, and tire tracks and rub marks existed on the fracture surface of a T-type crack. At α values but $\alpha = 1$, the fracture surface of an L-type crack was similar to that at $\alpha = 1$. Under in-phase loading, a crack propagated avoiding whisker, similarly to the case of out-of-phase loading. Also the fracture surfaces were rubbed each other and some wear debris could be seen.

3.6 Influence of out-of-phase loading on fatigue strength

At a higher stress of the matrix material, no influence of out-of-phase loading was observed on crack initiation and crack growth behavior, resulting in the same fatigue strength of the in-phase loading as that of out-of-phase loading. At a low stress level, however, a crack was initiated earlier and propagated faster under out-of-phase loading, resulting in lower fatigue strength under out-of-phase loading than under in-phase loading. Under out-of-phase loading, the maximum shear stress range ($\Delta\tau_{\theta}$) plane near the transverse direction has higher positive normal stress range than that near the longitudinal direction, and thus T-type crack was initiated, propagated, and finally brought about final failure. In this case, out-of-phase tension/torsion loading caused rotation of maximum principal stress, which induced an interaction of slip planes, resulting in severe fatigue damage. This was already reported in unreinforced metals^{(10),(11)}, and the severe fatigue damage caused a decrease in fatigue strength of the matrix material under out-of-phase loading than under in-phase loading.

As for the composite under both in-phase and out-of-phase tension/torsion loading, L-type cracks were initiated by whisker/matrix interfacial debonding at an early stage of about 10% of fatigue lives, and most of fatigue lives were dominated by a fatigue crack growth stage. At the same time, L-type crack growth rate under out-of-phase loading was smaller than under in-phase loading (see Fig. 11). This is a reason why the fatigue strength under out-of-phase loading was higher than that under in-phase loading.

In the case of matrix material under out-of-phase loading, T-type cracks initiated and propagated. However, for the composite material, L-type cracks initiated preferentially and propagated faster compared with a T-type crack because of anisotropy of the composite material; when an SiC_w/Al was subjected to uniaxial loading, crack growth rate in the T-L or R-L crack plane orientation was reported higher than that in L-T or L-R crack plane orientation^{(2),(3)}. This is a reason why an L-type crack initiated preferentially compared with a T-type crack, and propagated faster, although the positive normal stress range was smaller in the maximum shear stress range plane of an L-type crack. Moreover, a positive normal stress range of the L-type crack plane under out-of-phase loading was smaller than that under in-phase loading, resulting in lower crack growth rate under out-of-phase loading. This caused a higher fatigue strength of the composite under out-of-phase loading than that under in-phase loading.

4. Conclusions

Fatigue tests at a stress ratio R of 0.1 were performed in an SiC whisker reinforced A6061 aluminum alloy and its matrix material (A6061 aluminum alloy) under in-phase ($\phi=0^\circ$) and out-of-phase ($\phi=180^\circ$) combined tension/torsion loading at room temperature. The tests were conducted with various combined stress ratios $\alpha (= \tau_{\max}/\sigma_{\max})$, and crack initiation and propagation behavior was closely examined by using a replication technique. The investigation yielded the following conclusions:

(1) The quasi-static strength and fatigue strength of the composite under combined tension/torsion loading are superior to those of unreinforced matrix material.

(2) Fatigue strength of the matrix material under in-phase combined loading is higher than that under out-of-phase loading. However, the fatigue strength of the composite under in-phase loading is smaller than that under out-of-phase loading. This means that the strengthening effect by whisker reinforcement is more effective under out-of-phase loading than under in-phase loading.

(3) Under in-phase and out-of-phase combined loading, a crack that causes final failure is in the maximum shear stress range ($\Delta\tau_0$) plane near the longitudinal direction (L-type crack), except for the matrix material under out-of-phase loading. In this case, final failure is brought about by a crack in the maximum shear stress range plane near the transverse direction, i.e., T-type crack.

(4) As for the matrix material, a T-type crack under out-of-phase combined loading initiates earlier and propagates faster than an L-type crack under in-phase loading, resulting in lower fatigue strength under out-of-phase loading. A reason is that a rotation of principal stress under out-of-phase combined loading causes severe fatigue damage in the matrix material.

(5) As for the composite material, crack initiation life is about 10% of the fatigue lives, and most of

the fatigue lives are dominated by a fatigue growth stage. Under out-of-phase combined loading, an L-type crack initiates preferentially and propagates faster compared with a T-type crack because of anisotropy of the composite material, although a positive normal stress range in the L-type crack plane is smaller: in the case of the composite, the final failure is brought about by an L-type crack under both in-phase and out-of-phase loading. Moreover, normal stress range of the L-type crack plane is smaller under out-of-phase loading than under in-phase loading, resulting in lower crack growth rate under out-of-phase loading. This is a reason why the fatigue strength of the composite is higher under out-of-phase loading than under in-phase loading.

References

- (1) Arsenault, R.J., *Mechanical and Physical Behavior of Metallic and Ceramic Composite*, (1988), p. 279, *Risø National Laboratory*.
- (2) Shang, J.K. and Ritchie, R.O., *Metal Matrix Composites: Mechanisms and Properties*, edited by Everett, R.K. and Arsenault R.J. (1991), p. 255, *Academic Press*.
- (3) Hirano, K. and Takizawa, S., *Trans. Jpn. Soc. Mech. Eng.*, (in Japanese), Vol. 55, No. 511, A (1989), p. 373.
- (4) Komai, K., Minoshima, K. and Ryoson, H., *Composi. Sci. Tech.*, Vol. 46 (1993), p. 59.
- (5) Komai, K., Minoshima, K. and Yoshida, G., *Trans. Jpn. Soc. Mech. Eng.*, (in Japanese), Vol. 60, No. 572, A (1994), p. 1080.
- (6) Ishii, H., Yano, A. and Tohgo, K., *Jour. Soc. Mater. Sci., Japan*, Vol. 45 (1996), p. 60.
- (7) Hihara, L.H. and Latanision, R.M., *Corrosion*, Vol. 48 (1992), p. 546.
- (8) Tsai, S.W., *Air Force Materials Laboratory Report, AMFR-TR-66-149*, (1966).
- (9) Kanazawa, K., Miller, K.J. and Brown, M.B., *Jour. Eng. Mater. Tech.*, Vol. 99 (1977), p. 222.
- (10) Chen, X., Gao, Q. and Sun, X.F., *Fatigue*, Vol. 16 (1994), p. 221.
- (11) Socie, D., *Jour. Eng. Mater. Tech.*, Vol. 109 (1987), p. 293.