Cyclic Deformation and Low Cycle Fatigue Behavior in a 6061Al/22vol% SiC Whisker Composite

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A 6061Al matrix composite reinforced with 22vol% SiC whiskers and the unreinforced matrix alloy in different aged conditions were examined at the ambient temperature. Total strain controlled cyclic deformation under fully-reversed loading and low cycle fatigue properties were measured. The mechanical test results demonstrated that the composite materials in different aged conditions cyclically hardened at the applied strain amplitudes, typically at 0.4%, 0.6% and 0.8%. The underaged composite specimens showed the most pronounced cyclic hardening, while the overaged composite only hardened to a limited amount at the first a few cycles. It has been found that the addition of SiC whiskers into the 6061Al increased the cyclic stress to the largest extent in the underaged condition while to the smallest in the overaged. The low cycle fatigue resistance of the composite to cyclic straining was found to be inferior to that of the unreinforced matrix alloy. When the saturation cyclic stress amplitude is considered, however, the composite material showed superior fatigue strength to the matrix alloy in this low cycle fatigue region. The experimental phenomena are interpreted in terms of the result of the electron microscopy and the fractography of the fatigue failed samples.

Keywords: metal-matrix composite, 6061Al/SiCw, cyclic deformation, low cycle fatigue, fatigue life, fatigue strength

I. Introduction

Discontinuously reinforced metal-matrix composites have seen some successful structural application, such as in automobile industry. For instance, the material used in the present study, Al/SiCw composite, is now being put to use in motor parts of Suzuki engines. A detailed understanding of the resistance of the material to cyclic deformation and low cycle fatigue fracture is required for further extending its applications in engineering, particularly where large deformation or thermal shock are unavoidable. Whereas the fatigue strength and the fatigue crack growth behavior of the metal matrix composites have been extensively documented in the literature⁽¹⁾⁻⁽⁶⁾, limited effort has been made on the cyclic deformation and low cycle fatigue properties of this type of materials. Llorca et al. have conducted an experimental and numerical study of cyclic deformation in metal-matrix composites⁽⁷⁾. With emphasis being placed on the micromechanics modeling in this paper, the constrained matrix deformation in cyclic loading conditions was considered, while the cyclic hardening and softening behavior was characterized. From a study on the low-cycle fatigue microcracking behavior in a 2124Al/SiCw composite⁽⁸⁾, Sakaki et al. reported that the crack size distribution and the crack density depend on stress

amplitudes and on the number of cycles. Recently, Han et al. have reported that the SiCp/Al composite showed continuous cyclic softening after initial hardening⁽⁹⁾, while discussing the effect of particle size on the cyclic deformation and low cycle fatigue strength.

The understanding of the cyclic deformation and low cycle fatigue characteristics is yet far from complete. Further study on many aspects, such as the effect of matrix aging treatment on the stress response to cyclic straining, on fatigue life, on cyclic stress-strain behavior as well as low cycle fatigue life, are required. The objective of the present study is to investigate the cyclic deformation behavior and estimate the low cycle fatigue strength of a 6061/SiCw composite in underaged, peakaged and overaged conditions.

II. Material and Experimental Procedures

2.1 Material and specimen

The material used in the present study was a 6061Al matrix composite reinforced with 22vol% SiC whiskers, fabricated using a high pressure infiltration technique⁽¹⁰⁾. For the purpose of comparison, unreinforced 6061 Al alloy was also prepared in the same fabrication route as for the composite. The chemical composition of this aluminium alloy is given in Table 1.

Both the composite and the unreinforced materials were

Table 1 Chemical composition of the matrix 6061Al alloy

Si	Mg	Cu	Fe	Mn	Zn	Ni	Ti	Cr	Sn
0.80	1.07	0.23	0.26	0.07	0.07	0.03	0.02	0.07	0.00

heat treated to underaging, peakaging and overaging conditions. Solid solution treatment was performed at 803K for 9ks followed by water quenching. The composite sample blanks were then heated at 450K for 1.8ks, 21.6ks and 180ks, to produce the underaged, the peakaged and the overaged materials, respectively. The aging for the unreinforced 6061Al alloy was performed at the same temperature of 450K, whereas the time was chosen to be 3ks, 36ks, and 180ks, respectively. The samples were furnace cooled to the ambient temperature after aging treatment. Low cycle fatigue test specimens, round bar-shaped with gauge sections of $\phi 6.35\text{mm} \times 15\text{mm}$ following ASTM recommendations (ASTM E606-92), were machined after heat treatment. The surface of the uniform-gauge sections of the specimens was carefully polished.

2.2 Testing procedures

A Shimadzu servo-hydraulic testing machine with a load capacity of 50kN was used for the present study. A special specimen fixture system was adopted to the testing machine as shown in Fig.1. The specimen was fixed through a hydraulic clamping system on both ends. In order to assure a good alignment of the loading system and to prevent the specimen from any possible bending moment exerted upon clamping, a Wood's metal pot was utilized. The alignment of the system was checked by means of a trial test specimen with longitudinal strain gauges placed at four equidistance locations around the uniform-gauge diameter. Cooling water circulation was used for cooling down the Wood's metal pot as well as the lower grip.

Fig.1 Schematic set-up of specimen fixture for low cycle fatigue tests.

An extensometer with gauge length of 10mm for strain measurement, was attached to the specimen. Axial total-strain was taken as feedback signal for strain control testing. Tests were carried out at fully reversed straining mode, i.e., $R=-1$. The cyclic straining of the sample started with the tensile loading. The testing temperature was uncontrolled ambient temperature.

The strain rate in the present study was kept to be constant at 10^{-2}s^{-1} for various strain amplitudes tested. In other words, the frequency for a certain strain amplitude was adjusted according to:

$$\dot{\epsilon} = 4 (\Delta\epsilon_t/2) f = 10^{-2}$$

where, $\dot{\epsilon}$ is the strain rate, $(\Delta\epsilon_t/2)$ is the total strain amplitude and f is the frequency. Since triangle wave form was used for the strain controlled testing, a constant strain rate was available during the complete loading cycle.

Single sample method was employed for the determination of the cyclic stress-strain curves. With a single sample, cyclic deformation was first performed at the lowest strain amplitude. Upon cyclic saturation, the strain amplitude is shifted to a higher level and the specimen continuously cycled. The saturation stress was taken as the cyclic stress corresponding to the applied strain. The strain amplitudes were chosen from 0.1%, with incremental interval of 0.1%. In cases where no apparent saturation in the cyclic stress was noticed, the stress at about 1/3 of the fatigue life was taken as the saturation stress at the strain amplitude.

Fracture surfaces and the gauge section surface morphology of the low cycle fatigue fractured specimens were examined with an SEM. TEM study was carried out on selected specimens with different loading history, using a 200kV H-800 type Hitachi electron microscope. The sample was sectioned along the loading direction of the specimen for preparing the foils. Ion-milling was utilized for the final thinning of the samples.

III. Experimental Results

3.1 Stress response to cyclic straining

Figure 2 (a-c) shows the stress response to cyclic straining for the composite in underaged, peakaged and overaged conditions, respectively. Plotted in the figure are the stress amplitude vs. the number of loading cycles at different constant total strain ranges, typically being 0.4%, 0.6% and 0.8%. The stress amplitude was taken as the average of the peak values of the stress in tension and in compression during the loading cycles.

From the figure it can be seen that the 6061Al/SiCw composite shows initial cyclic hardening at every strain amplitude during cyclic straining, which is true for all the aged conditions. Comparison among the figures indicates that the underaged composite exhibited the strongest hardening while the overaged the weakest. Whereas no apparent softening was observed in the underaged and peakaged composites, the overaged composite slightly softened just a few cycles after the initial hardening.

For comparison, Fig.3 summarizes the stress response to cyclic straining of the matrix alloy at underaged, peakaged and overaged conditions. The material at underaged condition indicated the most prominent cyclic hardening and the overaged the least in a similar way as shown by

Fig.2 Stress response to cyclic straining of the 6061Al/22vol% SiCw composite in (a)underaged, (b) peakaged and (c) overaged conditions.

Fig.3 Stress response to cyclic straining of the 6061Al alloy in (a)underaged, (b) peakaged and (c) overaged conditions.

composite. In the overaged material significant amount of cyclic softening can be seen (Fig.3c) well before the rupture of the specimen, especially when cycled at relatively higher strain amplitudes. The final softening of the specimen during cycling is attributed to the cracks initiated on the sample surface and their propagation, giving rise to a reduction in tensile stiffness of the sample.

3.2 Cyclic stress-strain curves

Figure 4a shows the cyclic stress strain curves of the composite and the matrix alloy at different aged conditions. Compared with the unreinforced material, it is found that the addition of SiC whiskers into the Al alloy increased the cyclic stress most effectively in the underaged condition and the least in the overaged condition.

Figure 4b shows parts of the monotonic tensile stress-strain curves of the tested materials. These curves were obtained at the same strain rate as that for the cyclic deformation. In the monotonic tension test in the comparable strain range, the peak aged material showed highest stress response. However, the composite and the unreinforced material in underaged and overaged conditions exhibited different flow stresses. In the matrix material, the underaged showed the lowest flow stress, while in the composite the overaged showed the lowest.

Fig.4 Cyclic stress-strain curves(a) and the tensile stress-strain curves at the low stress range (b) for the composite and the matrix alloy.

IV. Discussion

4.1 Cyclic hardening

When a material is cyclically strained, the response stress usually shows an increase or a decrease with loading cycles, which are called cyclic hardening and cyclic softening, respectively. For some material it may reach a stage where the stress remained constant after the initial hardening or softening, which is called cyclic saturation. The stress response to cyclic straining of a material depends on its initial microstructure and on the deformation history. In general, a well-annealed metal normally shows cyclic hardening and a cold worked steel shows cyclic softening. Dislocation mechanisms are frequently cited for the interpretation⁽¹¹⁾.

Comparison of the stress response curves in the previous section (Figs.2&3) indicates that the unreinforced 6061Al alloy exhibited the largest hardening effect (Fig.3a). In the case of composite, the material in underaged condition also indicates the strongest hardening (Fig.2a). The overaged materials, including the composite and the unreinforced Al alloy, however, hardened only to a very limited extent (Figs.2c&3c). The difference in cyclic stress response shown by the aging treatment may be attributed to the size of the resulting precipitates. In 6061Al alloy the main strengthening precipitate is the β phase (Mg_2Si). Normally the underaged microstructure is characterized by the GP zones. Such GP zones are shearable by the dislocation glide in deformation, resulting in low initial deformation resistance. With further straining during cyclic deformation, the dislocations multiply and the dislocation density increases, which causes cyclic hardening. With longer aging time or higher aging temperature, the GP zones grow to a transition crystal structure β' . This stage usually corresponds to the peakaged condition, with the maximum hardness and usually with the peak strength (Fig.4b). There still atom alignment along some interfaces between β' and the matrix. Finally the precipitates grow to sufficiently large size and the β' is transformed to the equilibrium phase β . From this stage the onset of precipitates coarsening starts, thereby causing the strength to decrease and this stage is defined as overaged condition. Fig.6, which is the TEM micrograph taken in the overaged 6061Al alloy, shows the large precipitates. When the material with the large unshearable precipitates is

Fig.5 The relationship between the applied total strain amplitude (a) and the saturation plastic strain amplitude (b) and the straining reversals to failure, showing the fatigue resistance to cyclic straining of the materials.

3.3 Low cycle fatigue life

The total strain amplitude as a function of the number of loading cycles to failure for the composite and the unreinforced matrix material are plotted in Fig.5a. It is evident that the fatigue lives for the unreinforced matrix alloy in different aged conditions, represented with open symbols in the figure, are longer than those for composite specimens.

The underaged and the peakaged composites exhibited similar fatigue lives, and this is also true between the underaged and peakaged matrix materials. The overaged materials, however, showed different behavior. The matrix material showed the poorest fatigue life in the overaging condition in contrast to the overaged composite which showed the longest fatigue life compared with the other differently aged materials. In other words, the strain-life curves for the overaged composite and for the overaged unreinforced Al alloy locate closest to each other in Fig.5a.

In Fig.5b the saturation plastic strain amplitudes are plotted against the number of cycles to failure. While main trends appear to be similar to Fig.5a, a significant difference was shown by the overaged materials. In the diagram, the line for the composite shifted to the upper region to that for the unreinforced Al alloy. This indicated that the overaged composite showed a higher low-cycle fatigue resistance in the overaged conditions, in terms of the plastic strain amplitude.

Fig.6 TEM micrograph showing precipitates in an overaged 6061Al alloy.

Fig.7 TEM microstructure in an overaged 6061Al/SiCw composite showing (a) the dislocations in matrix alloy near a SiCw whisker in the virgin material and (b) the dislocation cell configuration formed in a specimen cyclically saturated at a strain amplitude of 0.6%. Loading axis parallel to the foil plane.

strained, the dislocations interact immediately with such particles in the first quarter of cyclic straining. The continuous hardening behavior as shown by the underaged material can not be expected in this condition.

The materials in the present study showed initial cyclic hardening. The hardening rate decreases gradually with the number of loading cycles and somehow saturation stages are attained. The cyclic saturation implies that with further cyclic straining, the deformation resistance remains unchanged. In other words, the cyclic straining is accommodated by some reversible micromechanism in the material during cycling. Fig.7 shows the dislocation structures in the 6061Al/SiCw composite. In Fig.7a, where a SiC whisker with twin structure in an undeformed virgin material is shown, the presence of dislocations can clearly be noticed. The large difference in the coefficient of thermal expansion (CTE) between the matrix and the reinforcement, introduces a tensile residual stress⁽¹²⁾⁽¹³⁾ and dislocations⁽¹⁴⁾ in the matrix. When the material is cycled to saturation, for instance at a total-strain amplitude of 0.6%, the dislocation cell structure in the matrix is formed, as shown in Fig.7b. The fro-and-to movement of screw dislocations in the low

dislocation density interior of the cell accommodates the applied strain.

4.2 Reinforcement and precipitation strengthening

In a composite microstructure with a precipitation strengthening Al alloy as the matrix, actually two types of strengthening mechanisms cooperate concurrently contributing to the resultant property of the material. The exact mechanism by which the introduction of reinforcement mutually affects the aging strengthening, is worth the consideration of composite researchers.

By comparing the curves in Fig.4a with those in Fig.4b, it is evident that the incorporation of reinforcement (SiCw) affected the aging strengthening effects. In both the monotonic and the cyclic deformation, the unreinforced Al alloy possessed the lowest flow stress in the underaged condition, while the overaged showed a stress level close to that of the peakaged. In contrast, the overaged composite showed the lowest stress in the monotonic and cyclic stress-strain curves, and the underaged material showed much higher stress. Particularly, in the cyclic deformation, the

Fig.8 TEM microstructure in an overaged 6061Al/SiCw composite cyclically saturated at a strain amplitude of 0.4%. (a) A SiC whisker with twin structure showing precipitates on it. (b) The dislocation in matrix alloy and the interface decohesion. Loading axis parallel to the foil plane.

Fig.9 The cyclic plasticity variation during low cycle fatigue test for (a) the overaged composite and (b) the overaged matrix alloy.

saturation cyclic stress of the underaged composite was in fact found to be a little higher than the peakaged. The low stress response in the overaged composite and the affected superior stress in the peakaged composite could probably be caused due to the Al-SiCw interface effect. Due to the high dislocation density and high tensile elastic stress field near the interface, accelerated diffusion could promote the interface precipitation. In the case of overaging, interface coarse precipitates and the precipitate free zone (PFZ) near the interface was formed. This could be considered to be responsible for the interface weakening in the composite, which leads to the interface failure. Fig.8 shows the TEM micrographs taken from the overaged composite after cyclic saturation at a total-strain amplitude of 0.4%. Fig.8a shows a whisker with coarse precipitates on it and Fig.8b shows the interface decohesion after deformation. The interface weakening phenomenon mentioned here is consistent with the study in 7xxx Al alloy matrix composites^{(15) (16)}. However, Mahon et al.⁽¹⁷⁾ argued that overaging improved the load transfer in 2124Al alloy matrix composite by interface precipitation.

It can also be noted from Fig.4 that the strain hardening exponents for the composite either in the monotonic or in the cyclic stress-strain curves are much higher than those in the unreinforced matrix material. This high strain hardening exponent in composite could be attributed to the constraint on the matrix flow caused by SiCw. Such constraint induced hydraulic strain could be increased by either the tensile or the compressive straining, according to an FEM study⁽⁷⁾⁽¹⁸⁾ and an experimental study⁽¹⁹⁾.

4.3 Low cycle fatigue resistance

The data in Fig.5 indicate that the low cycle fatigue life of the composite is generally inferior to the unreinforced matrix alloy, when a certain strain is applied. It could be rationalized in terms of the drastic reduction in the ductility of the matrix

Fig.10 Saturation stress amplitude (half life stress for the case of no saturation) as a function of number of cycles to failure in cyclic deformation for the composite and matrix alloy, showing the low cycle fatigue strength.

alloy caused due to the incorporation of ceramic reinforcement into the matrix. As a matter of fact, improvement of strength at the expense of ductility is a general fatal disadvantage of many advanced materials.

The effect of overaging on the low cycle fatigue life is worth noticing. Whilst overaging imposes a negative influence on the fatigue life of the matrix alloy, it promises a positive effect on the fatigue life in the composite material. Further, the overaged composite even showed a superior fatigue life to that of the matrix alloy when plastic strain amplitude is considered (Fig.5b). Fig.9 shows the plastic

Fig.11 SEM micrographs showing the fractograph and the surface of fatigue failed specimen surface in the overaged material. (a) Fracture surface near the fatigue origin of the composite. (b) Specimen surface of the composite. (c) Fracture surface near the fatigue origin of the matrix alloy. (d) Specimen surface of the matrix alloy.

strain amplitude variation in total-strain controlled cyclic straining for the overaged composite (a) and the overaged matrix alloy (b). It is obvious that, the plastic strain amplitudes in the composite specimen are much higher than those in the unreinforced matrix alloy for the equivalent total-strain levels. The improved near-interface PFZ mentioned above in the case of overaged composite material could possibly account for this phenomenon. The existence of the weak layer in the matrix near the interface could be favorite site for the accommodation of the applied strain, in addition to the well-known early stage yielding in this type of composite⁽²⁰⁾⁽²¹⁾, as could also be noticed from Fig.4. It is also evident from Fig.9 that the plastic strain amplitudes were increasing slightly after the initial decrease. This also is an indication of cyclic softening consistent with the stress response shown in Figs.2&3.

So far we have discussed the fatigue resistance to cyclic straining, either in terms of total-strain or plastic strain. When the saturation stress amplitude (or the half-life stress when no apparent saturation is seen) at each strain level is plotted against the number of loading cycles to failure, the result can be represented in a form as shown in Fig.10. The result of fatigue life appears to be in contrast to Fig.5 where the composite specimens indicated much higher fatigue strength than the unreinforced matrix alloy. In other words, the composite showed not only superior high cycle fatigue strength, as it is well-known⁽⁶⁾, but also superior low cycle fatigue strength compared to the matrix alloy studied.

The difference in the fractography and surface morphology after fatigue can be seen in Fig.11. Fine fracture features in the area near the fatigue origin in the composite fatigue fractured at a strain of 0.4% can be seen in Fig.11a. In contrast, the matrix material have a much coarser fractographic appearance (Fig.11c). Fatigue damaged composite could be observed in the sample surface in Fig.11b. In the matrix material, on the other hand, surface slip bands can be seen (Fig.11d).

V. Conclusions

Based on the results from an experimental study of cyclic deformation and low cycle fatigue test on a 6061Al-22vol% SiCw composite and the unreinforced matrix alloy in different aged conditions, the following conclusions could be drawn:

1. The composite material showed cyclic hardening at various strain levels in different aged conditions. The underaged material showed the largest cyclic hardening potential and the overaged the smallest.
2. Incorporation of SiCw improved the cyclic stress as well as the monotonic stress. The effect was most pronounced in the underaged condition.
3. The fatigue resistance to cyclic strain of the composite was inferior to the matrix alloy in the total-strain controlled testing. In composite the overaged specimens showed the best cyclic plasticity, and hence the best fatigue resistance to cyclic strain.
4. The fatigue strength (stress) of the composite material was higher than the matrix alloy in the low cycle fatigue region.
5. The overaged composite material exhibited superior

cyclic plasticity, lower cyclic hardening and lower fatigue stress. This is attributed to the interfacial precipitation and widened precipitate free zone.

Acknowledgement

ZMS expresses his gratitude to the Japan Society for the Promotion of Science (JSPS) for providing the opportunity and financial support for him to carry out the present research work in Japan. Partial support from the Daiko Foundation (Japan) to this work is also appreciated.

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