FRACTURE BEHAVIOR OF A SICw/6061AL ALLOY COMPOSITE UNDER CYCLIC LOADING

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ABSTRACT

The fracture behavior of a SiC whisker reinforced 6061 aluminum alloy matrix composite under cyclic loading were investigated at both room and elevated temperatures with total strain controlled method. TEM and SEM were used to examine the microstructure and fracture surfaces of the specimens. The mechanical test results demonstrated that the composite materials maintained initial cyclic hardening. Under cyclic loading, the composite material failures with a mechanism of void's nucleation, growth and coalescence, which are near the end of SiC whisker reinforcements.

KEYWORDS: fracture behavior, cyclic loading, SiCw/6061Al, low cycle fatigue

1. INTRODUCTION

In order to reduce the fuel consumption and improve thermal efficiency of engines, aluminum matrix composites have been used for the new engine parts. For instance, the material used in the present study, SiCw/Al composite, is being used in motor parts of Suzuki engines[1]. However, a detailed understanding of the resistance of this material to cyclic deformation and low cycle fatigue fracture is required for further

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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 presented extensively in the literatures[2]-[5], limited results have been reported on the cyclic deformation of this type of materials, especially, at elevated temperature. The present study is to investigate the fracture behavior of a SiCw/6061Al composite and its matrix under cyclic loading.

2. MATERIAL AND EXPERIMENTAL PROCEDURES

2.1 *Material and specimen*

The material used in the present study was a 6061 Al alloy matrix composite(MMC) reinforced with 22vol% SiC whisker, fabricated using a high pressure infiltration technique[2]. For comparison, a 6061 Al alloy(matrix) was also prepared in the same fabrication route as for (MMC). Both MMC and matrix materials were heat treated to the overaging conditions. Solid solution treatment was performed at 803K for 9ks followed by water quenching, then aged at 450K for 180ks to achieve overaged condition. The test specimens were machined with the loading axis perpendicular to the casting direction. The plate-shaped specimens of 80mm long, with gage section of 4×6×20mm, following ASTM (E606-92) recommendations were used for this study. The surface of the uniform-gage section of the specimens was carefully polished.

2.2 *Testing procedures*

A servo-hydraulic testing machine (load capacity: 50kN) was used in the present study. The tensile tests were performed in stroke controlled mode in accordance with ASTM E8M at an average cross head speed of 10^{-2} mm·s^{-1}. The cyclic deformation tests were performed in a fully reversed axial total-strain controlled mode. The strain rate was kept at 10^{-2}s^{-1} for various strain amplitude tests. Since triangular wave was used for the strain controlled testing, a constant strain rate was available during the complete loading cycle. The cyclic stress-strain behavior was studied with the incremental step method at different temperatures. The tests were carried out typically with a initial total strain amplitude, $\Delta\varepsilon_t/2$ of 0.075%. After 10 loading cycles, the total strain amplitude was increased by 0.075%, and the procedure was repeated. The tests were conducted in air at RT(293K), 373K, 423K and 473K. The specimens were heated in a resistance furnace with a temperature accuracy of ±1K, and kept at the testing temperature for 3.6ks before starting a test.

2.3 *Microstructural analysis*

The fracture surfaces and gage section surfaces were examined in a scanning electron microscope (SEM), and an energy dispersive x-ray analysis system was used to determine the chemical compositions on some local area of fracture surfaces. Transmission electron microscope (TEM) was also used to study the microstructure of the specimens for different loading histories. TEM samples were sectioned near the fracture surface along the loading axis of the specimen. Ion-milling was utilized for the final thinning of the samples.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 *Mechanical behavior*

Figure 1 shows the stress-strain curves of MMC under cyclic and monotonic(tensile) loading at different temperatures. It can be seen that the stress response of MMC under cyclic loading were higher that those under monotonic loading, regardless at the elevated temperatures. Table 1 shows typical stress response to cyclic and monotonic straining for MMC and matrix with a strain of 0.60% at different temperatures. Both cyclic and tensile stress responses decreased with the increasing of testing temperatures, while, comparing with the matrix, MMC showed higher stress response and kept less cyclic hardening until 473K. The higher stress response and higher strain hardening exponent in the composite are attributed to the constraint of the matrix flow caused by the reinforcement of SiC whiskers. This has been confirmed by an experimental study [6] and an FEM study [7].

Table 1 The cyclic and monotonic(tensile) stress with a strain of 0.6% at different temperatures.

Fig. 1 The cyclic stress-strain and tensile stress-strain curves at low strain range for MMC at different temperatures.

Figure 2 shows the tress response to cyclic straining for both MMC and matrix at RT and 473K. The stress amplitude was taken as the average of the peak values of the stress in tension and in compression during the loading cycles. It is clear that MMC shows initial cyclic hardening at both temperatures during cyclic straining, and the cyclic hardening was more prominent at RT, which was followed by saturation and softening after a few initial hardening cycles. The matrix exhibits cyclic hardening at RT, however, when the temperature increase to 473K, it indicates softening from the starting.

Fig. 2 Cyclic stress amplitude of MMC and its matrix with different total strain amplitudes at RT and 473K.

The cyclic saturation implies that the deformation resistance remains unchanged with further cyclic straining. In other words, the cyclic straining is accommodated by certain reversible micromechanisms in the material during cycling. For MMC, due to the large difference in the coefficient of thermal expansion [CTE] between the reinforcement of SiC whiskers and the matrix, it introduces a tensile residual stress[8] and dislocations[9] in the matrix, especially in the vicinity of the whiskers, as shown in Fig. 3 a). When the material is cycled to saturation, for instance at 473K with total strain amplitude of ±0.45%, the planar-array dislocation structure is formed, as shown in Fig. 3 b). The fro-and-to movement of screw dislocations in the low dislocation density interior of the planar-array accommodates the applied strain. The presence of SiC whisker reinforcements induces changes in the matrix microstructure, *i.e.* high dislocation density, the smaller grain size [10], and the more homogeneous slip during cyclic deformation[11]. On the other hand, the matrix material is actually in an annealed condition with a lower dislocation density. When such a material is cyclically deformed, the increase in dislocation density and subsequent dislocation interactions can give rise to the initial hardening and finally cause cyclic stability. However, when the testing temperature and strain amplitude are increased, it exhibits softening from initial straining (Fig. 2 d)). This may be attributed to the cross slip of dislocations at higher temperatures (Fig. 5 c)), which caused the improvement of deformation flow. Furthermore, in Fig. 5 c) & d) intergranular failure can be noted clearly, which means that the matrix material failed in creep type at 473K. Therefore, it is not surprising that for the matrix cyclic softening occurs at higher temperatures.

Fig. 3 TEM microstructure in MMC showing: (a) the dislocations in matrix near a SiCw in the deformed sample, and (b) the planar-array type dislocations configuration formed in a specimen after cyclic straining at 473K.

3.2 *Fracture behavior*

The fracture surface morphology after cyclic straining (low cycle fatigue) of MMC and the matrix were shown in Figs. 4 and 5, at RT and 473K, respectively. It is notice that the fracture features of MMC are much finer than those of the matrix, regardless the different temperatures. And, for MMC, no evident slip line can be seen at the surface, while the microcracks perpendicular to the loading direction can be clearly seen from Figs. 4 a) and 5 a). It could be considered that since the addition of SiC whiskers introduced high density of dislocation and fine grain sizes, the cross and long distance slip of dislocations can hardly take place, even at high temperatures. Also, it can be seen that the SiC whiskers were exposed on the fracture surface (Figs. 4 b) and 5 b)), and such SiC whiskers were pulled out of the fracture surfaces (which were covered with the matrix material examined by EDAX). This demonstrates that the failure of MMC was predominantly through the matrix and not along the SiC whisker-matrix interface. The same behavior is reported for A2124 matrix composite[12]. In order to reveal the nucleation sites for voids in MMC material, the samples were sectioned near the fracture surface after cyclic straining and examined with TEM. Fig. 6 showed three kind of voids nucleation in composite. They are around the end of whiskers (Fig. 6 a)), at the corners between the cross whiskers (Fig. 6 b)), and at the whisker break (Fig. 6 c)), in the matrix. This feature seems to be because of large stress concentration at the end of whiskers [7][13], which causes intense plastic straining in the nearby matrix and leads to void initiation at the corners. Moreover, the large precipitates on the SiC whiskers (Fig. 6 c), arrow marks) have a notch effect and cause the whiskers broken[14] when the stress increases up to a certain level, then it will become a void. It is clearly noticed that void growth involves the emission of matrix dislocations from the whisker end. This can be considered as follows. Under the cyclic straining, the matrix around the whiskers has undergone extensive sliding. This observation reveals the possibility of the matrix debonding in the immediate vicinity of the whiskers where the tensile hydrostatic stresses are high enough to cause the whisker pull-out with the coalescence of voids. Therefore, the composite seems to be fractured mainly due to nucleation, growth (include the voids merge) and coalescence of the voids in the matrix around

Fig. 4 SEM micrographs for MMC(a & b) and the matrix(c & d) cyclic deformed at RT, a) & c) specimen surface; b) & d) fracture surface.

Fig. 5 SEM micrographs for MMC(a & b and the matrix(c & d) cyclic deformed at 473K, a) & c) specimen surface; b) & d) fracture surface.

Fig. 6 TEM microstructure in MMC after cyclic straining at 473K, showing the void initiation: (a) near the end of whisker; (b) between cross whiskers and (c) at the whisker breaks.

SiC whiskers.

On the other hand, the fracture of the matrix under cycle straining seems to be associated with slip and creep. When the test is performed at low temperature, the fracture of matrix displays striation and transgranular failure (Fig. 4 c) & d)), while when the testing temperature is raised to 473K (Fig. 5 c) & d)), intergranular cavitation and microcracking generated mainly by the grain boundary diffusion. It can also be said that it is fatigue-creep fracture (Fig. 5 d)).

4. CONCLUSIONS

1) The SiCw/6061Al composite showed initial cyclic hardening with various strain levels from RT to 473K. Incorporation of SiC whiskers improved the cyclic flow stress as well as the monotonic flow stress at elevated temperature. These effects can be attributed to adding of whiskers into the matrix, which introduces high density of dislocations and constrains the matrix flow, aiding the composite to keep initial cyclic hardening and high stress until 473K.
2) Under the cyclic straining, SiCw/6061Al composite was found to fail in a mechanism of initiation, growth and coalescence (include merge) of voids in the matrix around SiC whiskers or at the whisker breaks, finally it makes the whisker pull-out from the matrix to cause the sample broken. While, the 6061Al alloy matrix failed in a manner changing from a pure fatigue to a creep/fatigue when the testing temperature increased.

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