IN SITU OBSERVATION ON FATIGUE FRACTURE OF MMC

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SUMMARY: The fatigue process of SiC fiber reinforced metal matrix composites is observed *IN SITU* within a scanning electron microscope. It is found that the cracks initiate early at stress concentrations caused by fiber fracturing. As the load cycles increase, the number of fractured fibers increase due to cavity formation in the matrix. Crack growth is affected by neighboring fibers. Almost every fiber fractured more than twice. The main fatigue crack in the specimen grows in a zigzag form by coalescence of transverse neighboring cracks. The longitudinal propagating of the cracks in the matrix runs close to the fiber-matrix interfaces. The crack initiation life is only about 4% of the entire duration. The apparent interfacial bonding strength is evaluated in terms of shear lag model.

Key Words: fiber reinforced aluminum matrix composite, *IN SITU* observation, fatigue crack initiation, crack propagation path, multiple cracking, fatigue life, interfacial bonding strength

INTRODUCTION

The continuous fiber reinforced metal matrix composites exhibit very good integrated mechanical behavior, especially excellent fatigue resistance. The high resistance to cyclic loading of advanced composites is of particular significance for aviation, spaceflight, automobile and other important structural applications. In construction design, reliability and lifecycle evaluation for the above application areas, fatigue performance is of particular concern. Since the “Bridging Mechanism“ on fatigue crack propagation of fiber reinforced metal matrix composites has been proposed [1], many research results support this hypothesis. Kazumi Hirano demonstrated that, in SiC_{CVD}/Al composite, the weakness of the interfacial bonding and the great difference in mechanical properties between the constituents of the composites are responsible for early propagation of fatigue crack along the interfaces. When the bonding is strong and the difference in mechanical properties of the components is small, interfacial debonding is rarely observed and propagation of fatigue cracks occurs by gradual failure of the neighboring fibers as is typical observed in SiC_{CVD}/Ti. Bowen et al studied fatigue crack propagation of SCS-6 (SiC_{CVD})/Ti-6Al-4V, and found that there was no clear relationship between the stress intensity at the crack tip and the crack growth rate. As the crack mouth opens, the crack wake is associated with a “bridging“ mode and the crack growth rate decreases. This is known as direct evidence of the bridging mechanism [2]. Yang Nihong et al found that in SiC_{CVD} (SCS-2)/6061Al during fatigue the crack propagates always along the interfaces of the fibers and matrix. They considered that the most important factors that impede the crack propagation are propagation along interfaces and the bridging mechanism at the crack tip area. The local strain energy is dissipated by the crack interfacial debonding, and the effective stress intensity factor there is reduced [3,4]. Bowen and Yang also found the crack-arrested phenomenon, and the rest period is quite long. The decrease in crack propagation rate was observed, too, at lower stress level for the same type of composite. The similar phenomenon is also found in rolled Al-Li alloy where the crack plane is perpendicular to the rolling plane [5]. Analysis demonstrates that this is related to the laminar microstructure. The laminar structure is made up of alternating strong and weak layers, and between the layers there are interfaces with moderate strength. Due to the weak interfacial bonding in some composites investigated by researchers, in these studies the macroscopic mechanical properties are not all so ideal, thus the effectiveness of the constituents, say, advanced fibers, is not satisfactory, especially the higher strength silicon carbide fiber and boron fibers, etc. Although there has been a great amount of research on the fatigue characteristics of metal matrix composites, the micro-mechanisms of fatigue crack initiation, crack propagation as well as final failure have not been quite understood. This is partly due to the complexity of the composite systems and the different fabrication processes that results in different mechanisms. This paper makes a direct survey to the fatigue process in a microscopical scale in order to determine the process of fatigue failure and understand more profoundly the composite materials, and provide a sound foundation for materials design and applications.

MATERIALS AND EXPERIMENTAL PROCEDURES

The material (SiCpcs/Al) used in this work was fabricated with ultrasonic wave-aided liquid-phase infiltration. The fiber number of one roving is 500, with a commercial name of *Nicalon*, the average diameter of the fibers is 15μm. The volume fraction of the fibers in the composite filament samples with a dimension of 0.45mm is about 45%, and the matrix is commercial aluminum. The gel-removed fibers are selected and the water-cooling process is used after infiltration. Table 1 shows some typical mechanical properties of the filaments. The length of the fatigue specimen is 45mm, including the grip region of 17mm at both ends. The surface with an area of 2.5×0.25mm to be observed was prepared by mechanical grinding and polishing and was chemically etched or washed in acetone. The tension and fatigue tests were carried out on an appropriative stage, which is computer-controlled and installed in a scanning electron microscope of JEM-35C.

Table 1. Normal Mechanical Parameters of Composite filaments

Cooling medium	Diameter (mm)	Ultimate strength, MPa	Elastic modulus, GPa
Water	0-45	1290-1410	127-137

The surface morphologies were observed and recorded during cyclic loading. A programmed loading system is used having a maximum load of 50N, minimum load of 5N (stress ratio of 0.1). The loading frequency is from 0.25 to 0.5Hz. Every 20 to 50 cycles of load, the change in the morphology of the selected surface was recorded photographically.

OBSERVATIONS OF CRACK INITIATION AND GROWTH DURING FATIGUE PROCESS

Considering the characteristics of the crack initiation and growth during the load cycling, the fatigue process can be divided into three phases. (a) Breaking of some fibers and initation of cracks. (b) Secondary or multiple cracking of fibers and cracks in the matrix. (c) Connection of cracks and final failure.

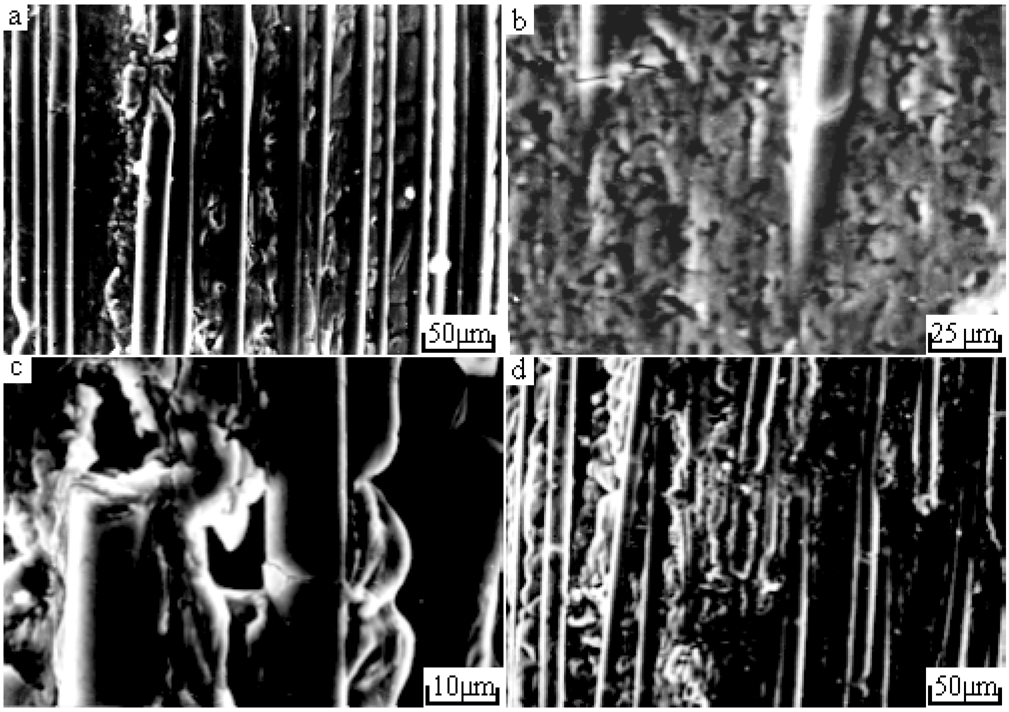

Fig. 1 Change in surface morphology during fatigue
a. Original surface, b. Fractures of the curved fibers, c. Cracked fibers beside the cavity, d. Secondary fracture of some fibers

Crack Initiation

Before fatigue loading, the original surface morphology was recorded and is shown in Fig. 1a. It is easy to find that some fibers were damaged during preparation, and most of the fibers are standing out of the matrix. A few cavities can also be found in the matrix. After loading for N=180 cycles, some striation-like surface patterns are observed in the matrix areas, and this area seems to increase with the number of loading cycles. This pattern is considered to be related to cyclic plastic deformation in the metal surface. The first crack in the fiber is found at N=280 cycles. The breaking of two fibers appear at the curvy point of the fibers. And some of the fracture surfaces are angled to the longitudinal direction of the fibers. After further cycling of tens of cycles, the fibers beside the cavities all break down (see Fig. 1 c). The secondary breaking of the fibers is at about N=330 cycles.

Multiple Cracking of Fibers and Crack Initiation in the Matrix

There are seven fibers fractured on the surface within a very small area of the sample at

N=400 cycles, and the cracking sites are concentrated in a limited region and accompanied by a very little propagation to the matrix. It is necessary to notice that the neighboring fibers fracture almost at different longitudinal sections, staggering a distance of several diameters of the fibers.

As the load cycling increases, the multiple cracking of the fibers are spreads to a larger area, and the length of the fragments of the fibers tends to a particular value. Meanwhile the matrix cracks formed by fiber fracturing are propagating in a small step (the mean value is 1/5 diameter of the fiber). Whereafter the progressing direction is oriented to longitudinal direction of the fibers (also the loading direction), deviating several micrometers from the fibers' surface. The longitudinal crack always goes along the midway between two fibers, tending to connect the neighbored cracks of the fibers between which the spacing is small (Fig. 2 a). Some small cavities newly appear in the matrix at N=520 cycles, which may be related to the propagating crack in the matrix (Fig. 2b).

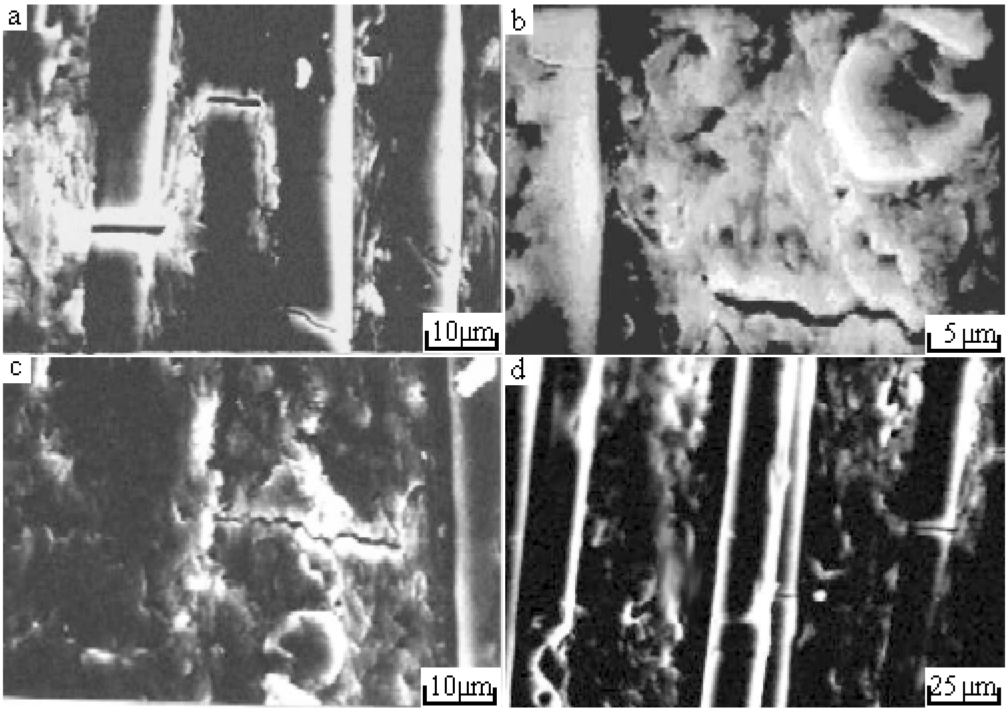

Fig. 2 Matrix crack initiation and connection

a. Longitudinal link, b. Cavities in matrix and linked to the close fiber crack, c. Matrix crack links to the fiber crack., d. Crack turns to fiber crack

After more than 100 loading cycles, a few neighboring cracks in the fibers get connected (Fig. 2 c) in the area of crack-densely distributed. However, in the other area within the observing surface, this is not a general case, the main process is the multiple cracking of fibers and extending into the matrix. At N=860 cycles the growth of isolated matrix cracks is clearly observed and most of the cracks deviate their original directions in such a way that their tips towards the fracturing points of neighboring fractured fibers (Fig. 2d).

Crack Connecting and Final Failure

After N=1000 cycles the change of the surface morphology becomes slow. The fracture events of the fibers decrease, instead of fiber cracks stretching into the matrix and axially connecting. The fiber-dense and crack-dense area evolves into major crack (Fig. 3 a). The axially linked cracks open and become deeper at N=2000 cycles. The second crack-dense area appears progressively, and is removed from the main crack by about three or four diameters of the fiber at N=5000 cycles (Fig. 3c). It is easy to see that all fibers have broken off.

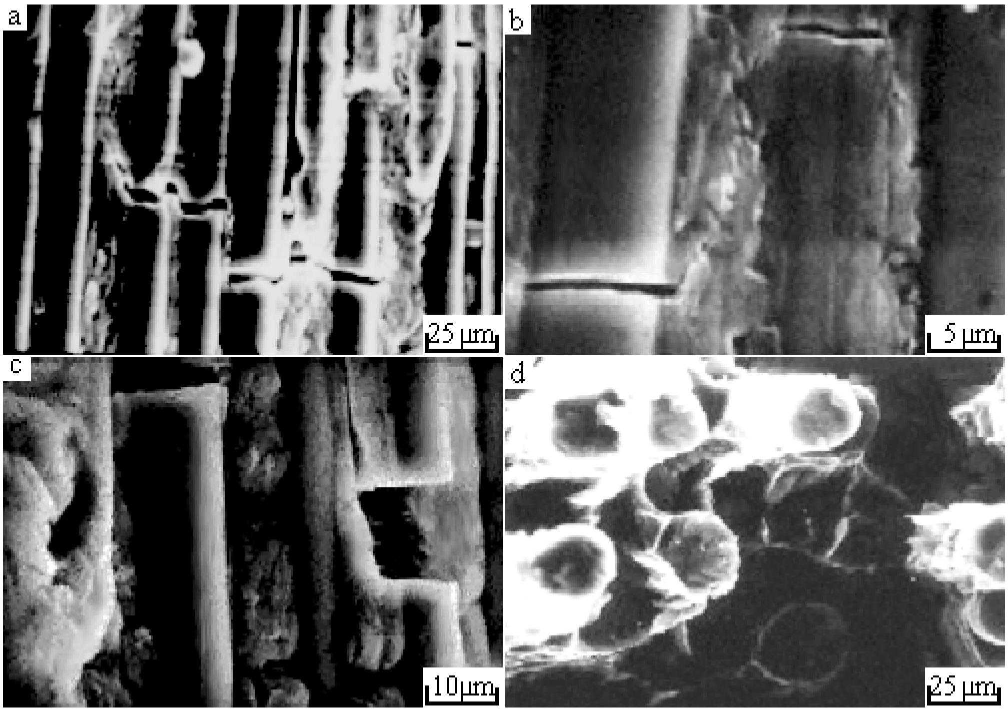

Fig. 3 Crack linkage and main crack forming characteristics
a. Crack-dense area evolves into main crack, b. Crack linkage in tilt modes, c. Crack opening, d. Fracture surface, show adhered aluminum on the fibers

When the coalescence of matrix cracks starts, the free fibers that appear at the outside of the composite filament also break after 7760 loading cycles (Fig. 3d). The main crack grows and opens in the main crack-dense area. At N=7950 cycles from the opened main crack the “bridging“ phenomenon by internal fibers is observed—the broken fiber pulling out from the matrix and some cycles later final failure occurs.

The fracture surface is microscopically quite rough. It is easy to identify a thin film of aluminum is adhered to the cylinder of each pulled fibers. The matrix around the fiber ends shows significant plastic rupture features—dimples and tearing ridges.

ON CALCULATION OF APPARENT INTERFACIAL BONDING STRENGTH DURING DYNAMIC FRACTURE

According to the shear lag model on fragment length versus the fracture strength of fibers, the shear strength, which is considered as the interfacial bonding strength in the case of interfacial failure [6], can be calculated. In the present situation this value can be calculated approximately with ignoring the residual stress field between the fibers and matrix, and the assumption of the shear face would be a cylindrical one with a radius of $\boldsymbol{r_0}$:

$$\boldsymbol{\sigma}_{int\,erficial} = \frac{\sqrt{3}}{2}\frac{\boldsymbol{\sigma}_{k2}}{\boldsymbol{l}_f / \boldsymbol{r}_0} \qquad (1)$$

where $\boldsymbol{\sigma_{k2}}$ is the critical fracture strength of the fibers and can be replaced with the mean strength of the fibers, $\boldsymbol{L_f}$ and $\boldsymbol{r_0}$ are the average final fragment and radius of the fibers. $\boldsymbol{L_f}/\boldsymbol{r_0}$ is measured to be 4.5. Taking $\boldsymbol{\sigma_{k2}}$ =2500MPa, the longitudinal shear stress is obtained to be 480MPa. Obviously, this value corresponds to the true fracture strength of the aluminum matrix. That is coincident with the fact that the cracks grow and longitudinally link only in the matrix. Moreover, the interfacial strength (bonding strength) in the present material is quite high compared with the strength of the matrix. In other words, the interfacial bonding strength of the present material is so high that the interfacial failure is not observed. This phenomenon is not common in the same type of composites. In fact, due to the inevitable fiber damages during its fabrication, such as clearing, extending, winding, passing mould, sinking and contacting the melt aluminum, and so forth, the actual average fracture strength of the fibers will decrease in some extent. So the above calculated shear strength is the upper limit of the interfacial shear strength, i.e., $\sigma_{interfacial} \leq 480$MPa. It is also found that some fragments are much shorter, at least $L_f / r_0 \approx 2.0$. It is obvious that the localized damage in fibers is a very important factor to influence the fracture behavior of the fibers. At the stationary condition, the filament is stretched and the similar results are obtained, in that case the calculated “interfacial debonding strength“ is about 433MPa.

CONCLUSIONS

Through *IN SITU* observation in SEM of fatigue process of SiC_{PCS}/Al, some interesting fracture phenomena are found:

The crack initiation life accounts for a quite small proportion of the entire life cycle of the material.

In unidirectional reinforced composites the fatigue cracks initiate at multiple sources, such cracks coalesce in crack-dense areas where the main crack formed.

Not under all circumstances, the fatigue cracks propagate along interface between the fibers and the matrix. If the fabrication is well controlled, the composites will be obtained with good interfacial state, therefore the cracks propagate longitudinally in the matrix near the interfaces.

The effect of the cracks in the matrix with low strength is very slight on fatigue behavior of the composite reinforced with high strength fibers and is only involved in the operation of crack linkage at the last stage of the fatigue life cycle, when compared with the matrix of higher strength.

Only in the last stage of the whole fatigue process can the bridging phenomenon by broken fibers be observed after the opening of the crack mouth.

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