JOURNAL OF MATERIALS SCIENCE **35** (2000) 5347–5351

Short thermal fatigue crack propagation behavior of alumina short fibre reinforced aluminum matrix composites

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Thermal fatigue resistance is one of the most important parameters to design engine materials. The thermal fatigue crack growth behavior of alumina short fibre ($V_f = 18$ vol.%) reinforced AlSi12CuMgNi aluminum alloy composite has been investigated under thermal cycling condition between room temperature and 280 °C. Initiation and propagation of thermal fatigue crack have also been discussed. The results show that in the range of short crack, the fibres play an important role in the path of thermal fatigue crack, and the crack propagation rate of composites is much larger than that of the matrix alloy. © *2000 Kluwer Academic Publishers*

1. Introduction

In recent years, the need for lighter materials with high specific strength and stiffness have led to the development of numerous composite materials as serious competitors to traditional engineering alloys. Aluminum metal-matrix composites are of great interesting. In metal matrix composites, the monotonic properties, such as strength and toughness, are improved by reinforcing a ductile matrix. The damage-tolerant properties, such as fracture toughness and fatigue resistance, suffered significant degradation for most of the composites. The latter properties are important for component reliability and design [1]. Many composites are often subjected to cyclic loading, so fatigue behavior has received significant attention. Up to now, some researchers have reported the fatigue crack growth behavior of metal matrix composites [1–9]. Comparing with the unreinforced matrix alloys, they found that the resistance of cast composites to fatigue crack growth is to be improved at the low ΔK region, deteriored at the high ΔK region, and comparable at the Paris region [4, 10]. Short crack behavior is different to the long crack behavior, for it is very sensitive to the microstructure. Various parameters, such as reinforcements size, volume fraction, morphology, matrix properties and interface strength have strong effects on the fatigue crack initiation, fatigue crack growth of composite [1, 3, 6]. As thermal cycling is one of the common service conditions for components, and there exists large difference of coefficient of thermal expansion between matrix and reinforcements, thermal fatigue behavior become an important branch of fatigue [11–15]. However, most of the researches are based on the high cycle fatigue behavior [1, 3–8], knowledge of low-cycle fatigue is lacking [2, 9], especially for thermal fatigue.

The main objective of this study is to investigate the short thermal fatigue crack propagation behavior in Al_2O_3 short fibre reinforced aluminum alloy composites under thermal cycling condition.

2. Experimental

The material under investigation is alumina short fibre (Al_2O_{3sf}) reinforced AlSi12CuMgNi aluminum alloy composites, produced by squeeze casting. The average size of reinforcing fibres is 0.1–0.2 mm in length, 5–9 μm in diameter, and their volume fraction is 0% (matrix alloy) and 18% (composites). These squeeze casted materials are subsequently heat-treated to T6 temperature condition. During this heat treatment with the temperature higher than that of stress-relieve annealing, most of the residual stress induced by cooling from squeeze temperature is removed. Physical properties of the investigated materials are shown in Table I [10]. The test specimens were ϕ 20 × 3 mm notch cuneiform plate. V notches, 2 mm in depth and 1 mm in width, were 180 degree symmetrical mechanical induced in each specimens.

Specimens were heated in a tube-furnace, when reaching the thermal cycling maximum temperature (T_{max}), they were dropped into water for cooling to room temperature. In order to accelerated thermal fatigue crack initiation, thermal cycling tests were performed firstly in the range of room temperature to 350 °C, and then T_{max} was decreased to 280 °C. Every cycle took 5 minutes, 4 min for heating and 1 min for cooling.

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TABLE I Physical parameters of matrix alloy and alumina short fibre

Material	Young elastic modulus E (GPa)	γ	Ultimate Tensile Strength (GPa)	Density ($g \cdot cm^{-3}$)	Melting temperature (K)	Coefficient of thermal expansion α ($10^{-6} \cdot K^{-1}$)	Thermal conductivity λ (w/mK)
AlSi12CuMgNi	70	0.33	0.25	2.7	850	23.6	~180
Al_2O_{3sf}	300	0.24	2.0	3.2	1600	7.7	~100

Using an optical microscope, short thermal fatigue crack growth behavior was observed, and the crack length was periodically measured. After thermal cycling test, thermal fatigue specimens were examined in a scanning electron microscope.

3. Results

3.1. Thermal fatigue crack propagation curve

In the test, crack behavior was investigated *only in short crack range*. Fig. 1 shows that thermal fatigue crack propagation curve of specimens. It can be seen that with thermal cycling continued, fatigue crack lengths of specimens get bigger, and crack propagation rate of composite is much larger than that of matrix alloy. The difference of crack growth rate versus thermal cycling times can also be seen from Fig. 1. Crack growth rate drops firstly remarkably and then slightly.

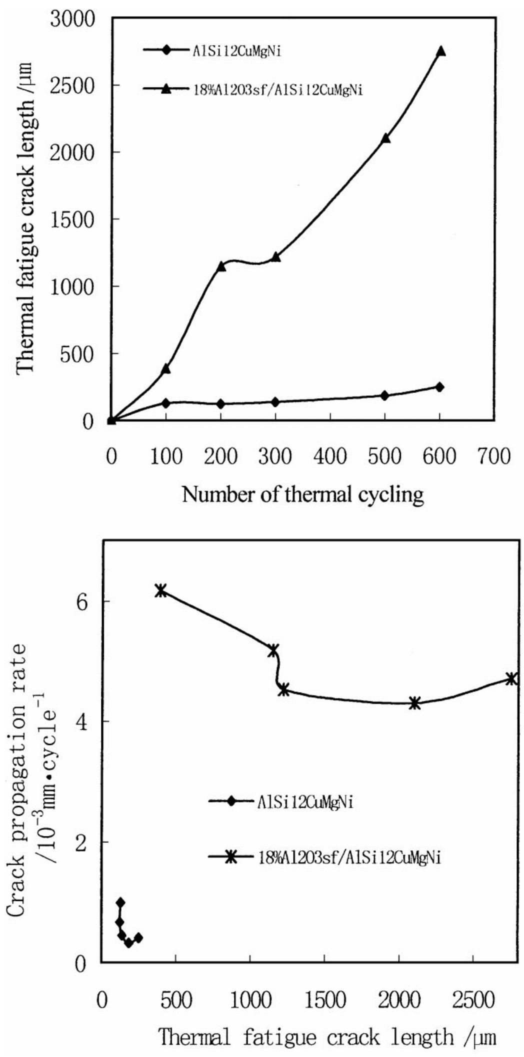


Figure 1 Thermal fatigue crack propagation curve.

3.2. Microstructure of thermal fatigue crack

Thermal fatigue crack initiation and propagation of specimens have been recorded, as shown in Fig. 2. It can be seen that thermal fatigue crack originates from the end of V notch for both specimens. Under thermal stress fatigue condition, fatigue crack of composite propagates in the form of single chief crack; however, for matrix alloy, thermal fatigue crack has notable branches. Another feature seen from Fig. 2 is that thermal fatigue crack propagates preferentially from the fibre reinforcements gathering region.

After test, specimens were examined in scanning electron microscope (Fig. 3). Thermal fatigue crack initiated phases of both samples are seen to be silicon phase, one of the matrix compositions. It can also be seen from Fig. 3 that for composite, fatigue crack propagate accompanied by the fibre/matrix interface debonding and fibre breakage, while for matrix alloy, crack propagation region deforms from the sample surface.

4. Discussion

4.1. Initiation of thermal fatigue crack

Composite is not a balanced thermodynamical system. From Table I, we find that the difference of coefficient of thermal expansion between alumina short fibre and AlSi12CuMgNi matrix alloy is nearly $16.0 \times 10^{-6}\ K^{-1}$. Under thermal cycling condition between room temperature to 280 °C, the maximum thermal strain may come to 0.4%, it is high enough for local matrix alloy plastical deformation. Through thermodynamically analysis, it can be found that the thermal stress status of sample's matrix change cyclically from residual tensile stress to compressive stress, and to tensile stress during thermal cycling. This results in accumulative plastically strain damage on matrix and interface. Some researchers have reported that clusters of reinforcement near the surface are the most probable sites of fatigue crack initiation [5, 6]. These regions have very high stress, like the end of V notch have. And as it is well known that silicon phase of matrix is poor at plastic deformation. The silicon phase at V notch end becomes one of thermal fatigue crack source.

Thermal fatigue is one kind of strain fatigue. Under strain fatigue condition, inhomogeneous sliding

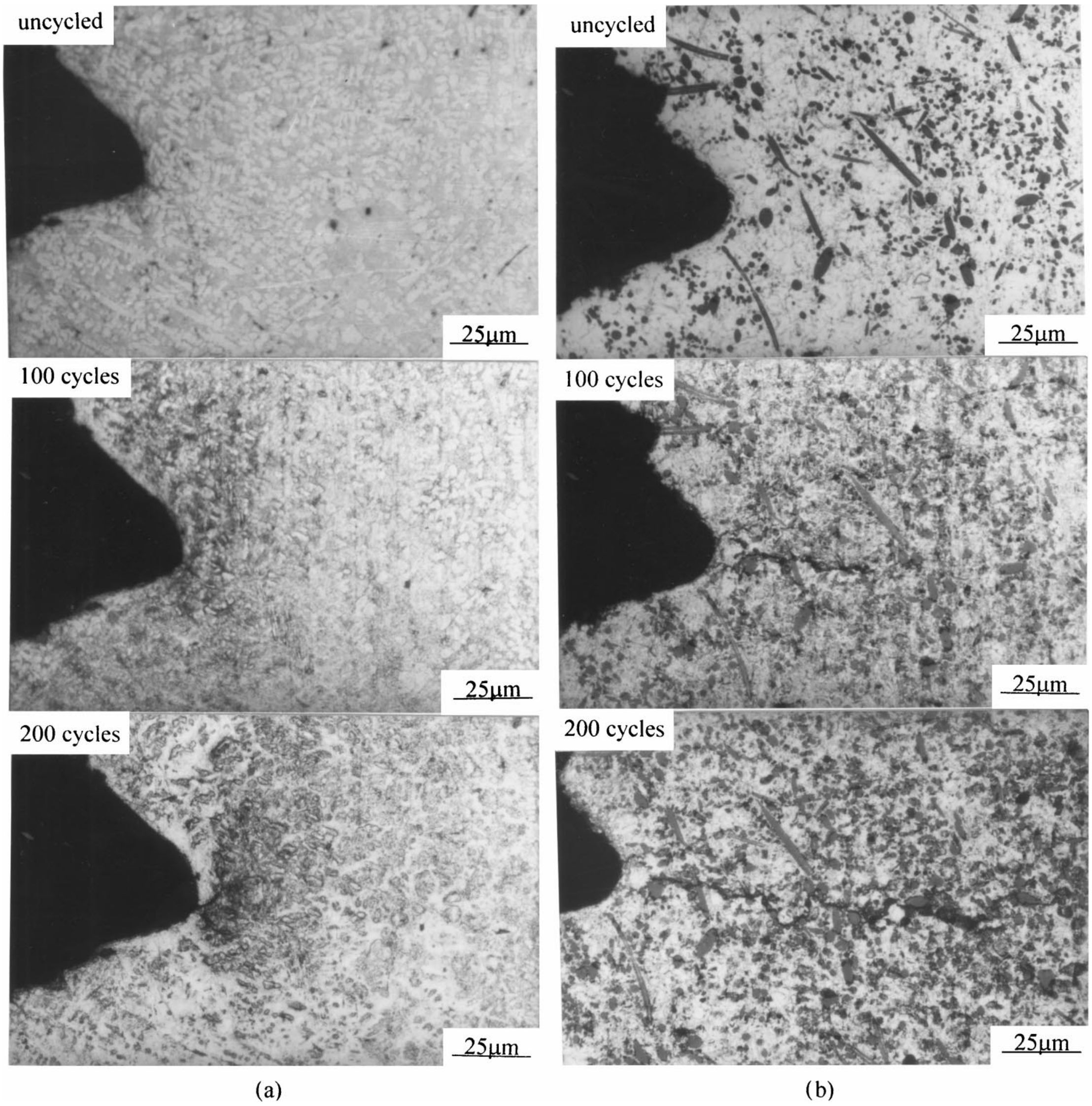


Figure 2 Optical micrograph of thermal fatigue crack. (a) AlSi12CuMgNi; (b) 18%Al_2O_{3sf}/AlSi12CuMgNi.

of aluminum alloy can form "micronotches" on the surface. It can also provide regions for fatigue crack initiation.

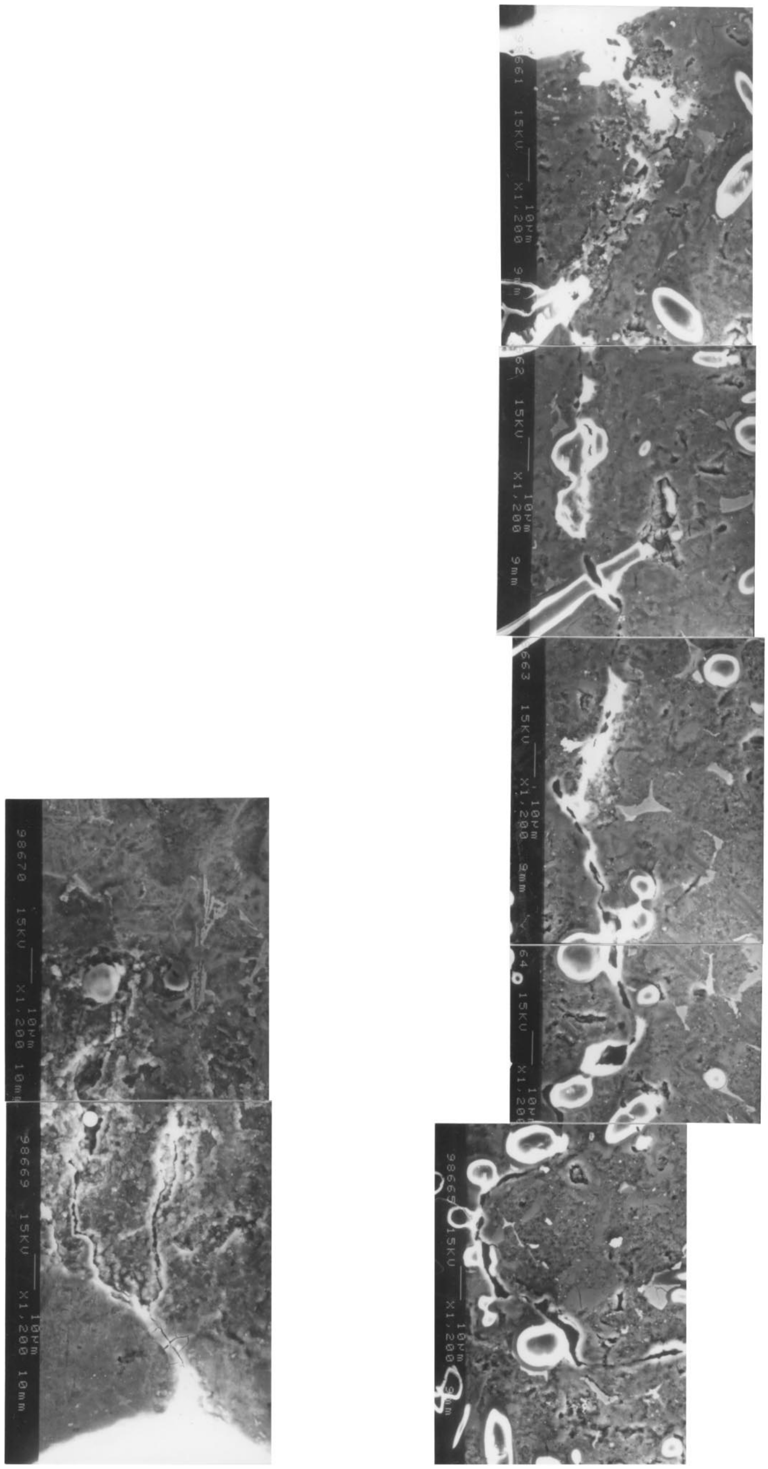
Refer to Fig. 3, the difference of both kind materials can be seen. Thermal fatigue crack of matrix alloy can derive from the above two region, while that of composite can only be seen to derive from the silicon phases, because high content of short fibre reinforcements restrain inhomogeneous sliding of aluminum alloy.

4.2. Propagation of thermal fatigue crack

Low-cycle fatigue life is controlled by ductility. It has reported that low-cycle fatigue behavior of the particulate composites was rather poor compared with that of the matrix alloy, and concluded that poorer ductility generally implies poorer life [2]. Thermal stress fatigue is a kind of dissymmetry stress low-cycle fatigue, and more complex. Temperature cycling range is a very important factor. The smaller temperature cycling range, the lower thermal cycling stress. This causes the fatigue crack growth rate to decrease.

In the test, thermal fatigue crack behavior has been studied in short crack range. Short crack is more sensitive to the microstructure [3, 6]. From Figs 2 and 3, fatigue crack is seen to go through clustering of short fibres and ends of fibres. Matrix can easily plastically deform in these high stress level regions. There exists large mechanical property difference between matrix and fibre, so that deformation of matrix will not coordinate to that of fibre.

Thermal stress acts on composites system cyclically. If the fracture strength of fibre is higher than interface strength, thermal fatigue crack goes through fibre region in the form of interface debonding, otherwise goes through fibre region in the form of fibre breakage. Under the investigated condition, thermal fatigue crack makes function on fibre in the above two ways (see Fig. 4). The strong interaction of thermal fatigue crack and fibre can reduce the stress of crack tip in varying degrees, and will constrain the crack propagation in further. In one words, the resistance of composites to thermal fatigue crack propagation would be improved, by strengthening fibre/matrix interface and improving fibre quality.



(a) (b)

Figure 3 SEM micrograph of thermal fatigue crack morphology. (a) AlSi12CuMgNi; (b) 18%Al_2O_{3sf}/AlSi12CuMgNi.

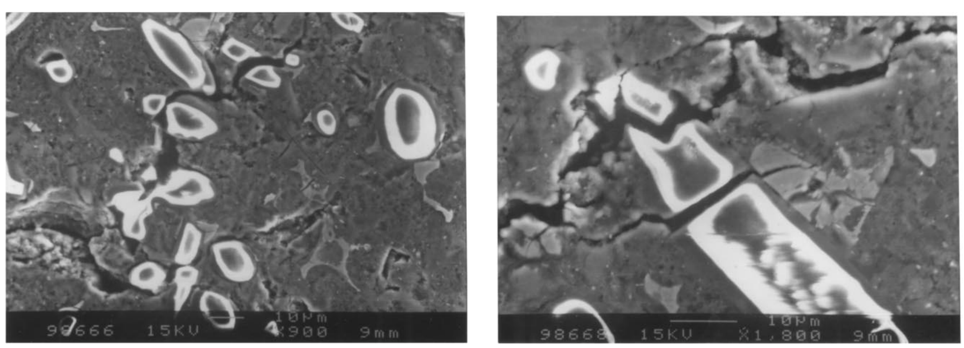


Figure 4 Interaction of thermal crack and alumina short fibre.

5. Conclusion

1. In the short thermal fatigue crack growth range, the resistance of 18 vol.% alumina short fibre reinforced AlSi12CuMgNi to thermal fatigue crack propagation is poorer than that of matrix alloy.
2. Under cyclic thermal stress condition, thermal fatigue crack acts on fibre reinforcements in two ways: fibre/matrix debonding and fibre breakage.

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Received 24 August 1999
and accepted 22 February 2000