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Low-Cycle Impact Fatigue of SiC_w/7475Al Composite

P. Yang, Y. Liu, and F. Xu

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Important uses in the future for metal-matrix composites are in aerospace, weaponry, and high-speed power plants in which the inertial force produced by great acceleration is a load of high strain rate. Therefore close attention is given to the mechanical behavior of a composite at high strain rates. This paper reports a study of the behavior and mechanisms of a SiC_w/7475 composite in low-cycle impact fatigue (LCIF). The LCIF and impact tension tests were conducted by using the push-pull impact fatigue apparatus developed by the authors, in which the loading assembly was actually a combination of a Hopkinson's pressure bar and an extension bar. In the apparatus the trapezoidal stress wave loads were produced. The strain rates in specimens may reach 400 s^{-1}. The results show that for a SiC_w/7475 composite, the strain-rate effects on yield stress, ductility, cyclic hardening and softening, $\Delta\varepsilon_e/2 - N_f$ relation, and transition life were slight. In low-cycle impact fatigue the cracks often initiated within or near the SiC particles, which mingled in the composite. The SiC_w/7475 composite was found to be less ductile than its alloy matrix; in low-cycle fatigue brittleness appears. Therefore great attention must be given to the behavior of the composite when it is used as a structural material.

Keywords aluminum alloy 7475, composites, impact, whiskers

1. Introduction

In recent years the ceramic particle and whisker reinforced aluminum-matrix composite has interested many people because it is cheaper and can be prepared and processed with ordinary technology. The mechanical properties of the composite provide considerable strength, higher elastic modulus, and excellent wear resistance. However, Davidson (Ref 1), and Zhu et al. (Ref 2) suggest that because additive rigid-brittle particles and whiskers interfere gravely in plastic deformation of the matrix and cause a change in crack initiation-propagation behavior, the plasticity and toughness of the composite obviously decreases, while the strength and elastic modulus increases.

Some investigation reports by Liu and Bathias (Ref 3), Levin and Karlsson (Ref 4), and Cho et al. (Ref 5) have been published on the mechanical properties of aluminum-base composites such as tension, wear, fatigue, and toughness. They have gained a considerable understanding of mechanical behavior and mechanisms.

However, the important use in the future of metal-matrix composites is in aerospace, weaponry, and high-speed power plants, in which the inertial force produced by great acceleration is a load of high strain rate. At high strain rates a characteristic mechanical behavior and mechanism appears. Therefore, in order to evaluate the properties of metal-matrix composites the authors have studied the stress-strain and fatigue behaviors at high strain rates. Based on the study of a SiC_p/Ly 12 composite (Ref 6), the authors have carried out an investigation on the behavior and fracture mechanism of SiC_w/7475 composites with a low-cycle impact fatigue (LCIF) and single impact tension test and attempted to evaluate the materials under high strain rate and to clarify the effect of reinforcement shape on mechanical properties.

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2. Experimental Method and Materials

The LCIF and impact tension tests were conducted by using the push-pull impact fatigue apparatus developed by the

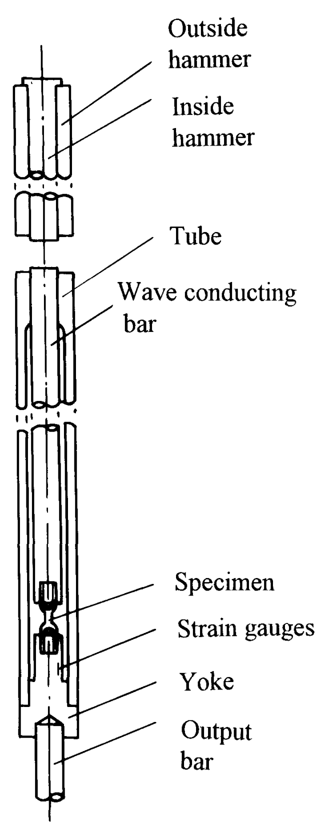


Fig. 1 Loading assembly

authors, in which the loading assembly is actually a combination of a Hopkinson's pressure bar and an extension bar (Fig. 1). In the apparatus the trapezoidal stress wave loads were produced. The strain rates in specimens can attain 400 s^{-1}. The testing principles and the determination method of stress strain are identical to those described in Ref 7.

In order to clarify the effects of strain rate, ordinary low-cycle fatigue (LCF) was conducted in parallel by using an Instron 1342 electronic-hydraulic testing machine with a trigonal wave function and strain controlled at 0.2 Hz frequency. In order to unify testing conditions, the specimens of uniform size and shape (Fig. 2) were used in low-cycle impact fatigue (LCIF), LCF, impact tension, and static tension tests.

The experimental material was a SiC whisker-reinforced aluminum alloy 7475 Al [AlZn5.5MgCu(A)]. The content of the SiC whisker was 20 vol%. Table 1 lists the main properties of the reinforcing β-SiC whisker. The composite was fabricated by the squeeze casting method, which was then subjected to two cycles of hot extrusion into a 12 mm diameter cylindrical bar. The tensile strength of the composite in the form of extrusion was 490 MPa, which was close to that of SiC_p/Ly12. In order to compare with SiC_p/Ly12 on the same strength level, the extruded SiC_w/7475 composite was used for the present study.

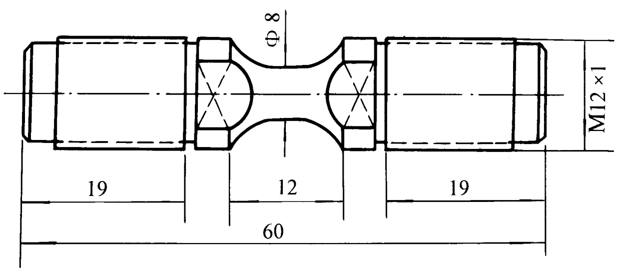


Fig. 2 Specimen (dimensions are in mm)

3. Results and Discussion

3.1 Static Tension and Impact Tension

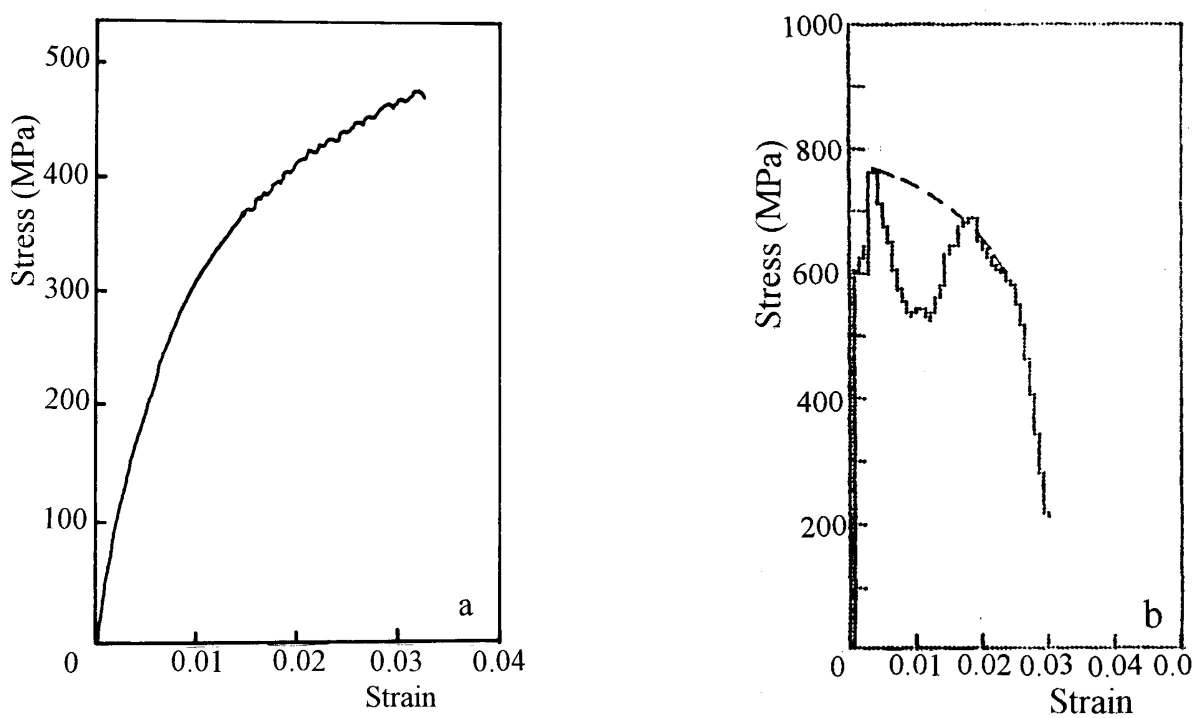
Figure 3 shows the typical stress-strain curves for the SiC_w/7475 composite in static tension and impact tension.

The static tension curve (Fig. 3a) shows that when the composite yields, the load pops in and out repeatedly, forming a sawtooth shape; thus the authors infer that during plastic deformation a noncontinuous fracture process inside the composite occurred. The mechanism is discussed in section 3.4.

The impact tension curve (Fig. 3b) was similar to that of metallic materials (Ref 7). In the curve there are periodic stress falls forming an attached oscillation, as shown by the solid line. This was not a typical behavior of the materials, so a smoothing procedure was undertaken, as shown by the dashed line.

Table 1 Properties of the SiC whisker

Diam., µm	Length, µm	Length/diam.,	Density, g/cm^3	Tensile strength, GPa	Elastic modulus, GPa
0.1 to 10	30 to 100	50 to 200	3.19	3 to 14	450



(a)

(b)

Fig. 3 Stress-strain curves in (a) static tension and (b) impact tension

Table 2 presents mechanical properties of the $SiC_w/7475$ composite, in which the mechanical properties of $SiC_p/Ly12$, containing 20 vol% particulate SiC, are also presented.

In impact tension the flow stress was raised; at 0.6% permanent deformation the overstress ($\sigma_{yD}/\sigma_y - 1$) of $SiC_w/7475$ was approximated to 0.09, which approaches that of Ly12 duralumin (0.1), but is much lower than that of low-carbon steel (1.6), stainless steel (1.0), and brass (0.6). It was found that aluminum-base alloys and aluminum-matrix composites all possess a lower overstress, which affects their LCIF behavior.

3.2 Cyclic Hardening and Softening

In LCF a slight cyclic hardening occurred in the $SiC_w/7475$ as in the $SiC_p/Ly12$ composite. However in LCIF at different strain amplitude, the cyclic stability appeared (Fig. 4).

Cyclic hardening (softening) results from an algebraic sum of hardening and softening in fatigue process. Here the hardening is intrinsic for the matrix alloy 7475 Al, and the softening is due to initiation and growth or a large number of microcracks in the entire stressed volume. The microcrack initiation mechanisms are due to the break of debonding of SiC whiskers and mingled SiC particles. Under the repeated high amplitude stress wave loads, the brittle SiC whiskers are easy to break. When the microcracks increase to the extent to offset the hardening action of the matrix, a cyclic stability appears. Due to a small cyclic hardening capacity of the 7475 Al matrix, the $SiC_w/7475$ composite exhibits a slight cyclic hardening in LCF and cyclic stability in LCIF.

3.3 Fatigue Life

By plotting $\Delta\varepsilon_e/2$ and $\Delta\varepsilon_p/2$ at 50% N_f against the cycles to failure N_f (Fig. 5), it was shown that their relations in both LCF and LCIF all conformed to Coffin-Manson law in the $SiC_w/7475$ composite as in metallic materials. For the $\Delta\varepsilon_e/2 - N_f$ relation, the data of both LCF and LCIF lay on the same data belt that was corresponding to a lower overstress for the composite.

The $\Delta\varepsilon_p/2 - N_f$ curve of LCIF was lower and parallel to that of LCF. In comparison with the $SiC_p/Ly12$ composite, it was shown that in LCF the $\Delta\varepsilon_e/2 - N_f$ curves almost overlap for the two composites. In both LCF and LCIF the transition lives of the two composites were identical.

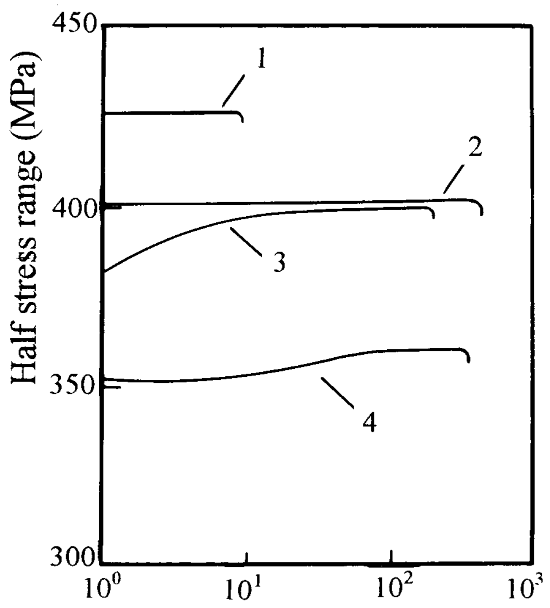


Fig. 4 Cyclic hardening-softening behaviors of $SiC_w/7475$ composite in low-cycle fatigue (LCF) and low-cycle impact fatigue (LCIF). (1) LCIF $\Delta\varepsilon_T/2 = 0.0067$. (2) LCIF $\Delta\varepsilon_T/2 = 0.0035$. (3) LCF $\Delta\varepsilon_T/2 = 0.0050$. (4) LCF $\Delta\varepsilon_T/2 = 0.0043$

3.4 Fracture Mechanism

A scanning electron microscopy (SEM) analysis of the longitudinal section showed that in the $SiC_w/7475$ composite the whiskers were different lengths and arranged without preferential orientation. Some broken whiskers and a few of particulate

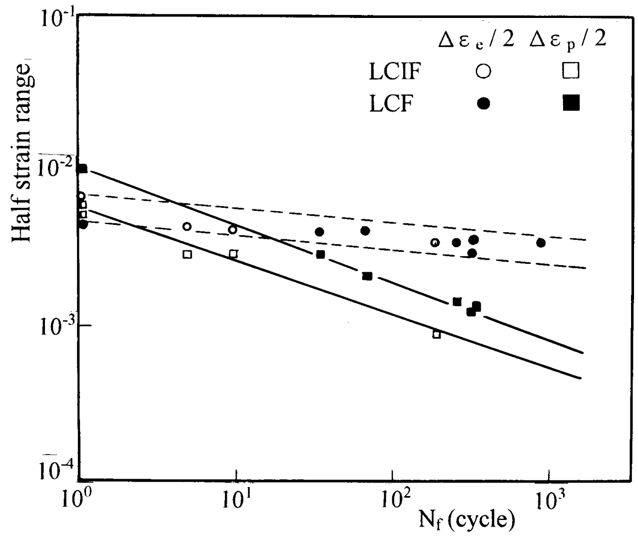


Fig. 5 Relationship between strain amplitude and cycles to failure in LCF and LCIF of $SiC_w/7475$ composite

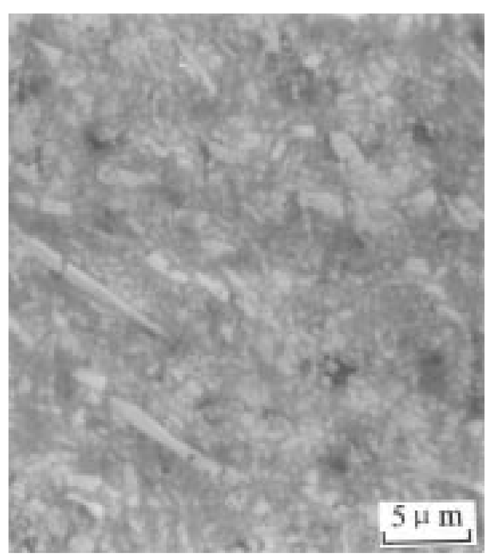


Fig. 6 Longitudinal section of untested specimen

SiC also appear in the section (Fig. 6). A SEM fractography analysis showed that in static tension the fracture surface consisted of shallow dimples with broken whiskers in the bottoms. No pulled out whiskers were observed (Fig. 7). The two kinds of areas can be distinguished by careful observation. In clumps of whiskers the fracture surface was even; in these areas a small plastic deformation occurred before fracture. Around this area the fracture surface was ridged, indicating a larger plastic deformation. Thus the basic fracture process of SiC_w/7475 composite in static tension can be inferred as follows. When the load exceeded the elastic limit of the matrix, a flow occurred in it. In the rigid SiC whiskers the deformation could not keep

Table 2 Mechanical properties of SiC_w/7475 and SiC_p/Ly12 composite

	Static tension		Impact tension		
	Tensile strength (σ_b), MPa	Elongation (δ), %	Tensile strength (σ_{bD}), MPa	Elongation (δ_D), %	Modulus of elasticity, GPa
SiC_w/7475	490	1.3	731	2.2	103
SiC_p/Ly12	470	2.0	820	2.0	100

All the data are for the mean value in three tests. In the SiC_w/7475 and SiC_p/Ly 12, the subscript *W* and *P* mean that whiskers and particles reinforce respectively.

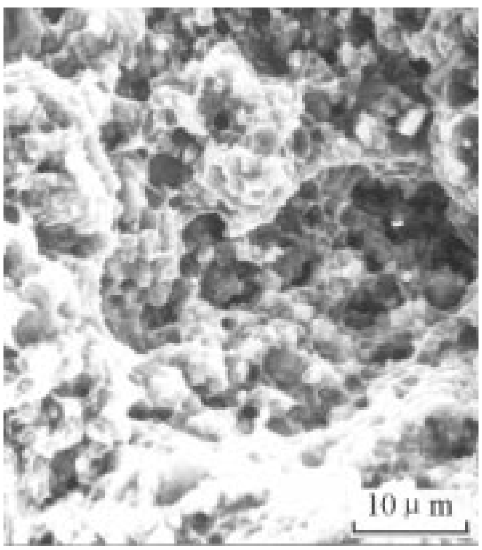


Fig. 7 Fracture surface in static tension of SiC_w/7475 composite

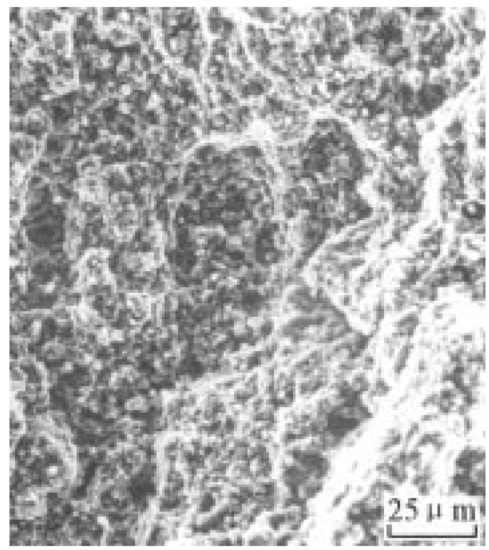


Fig. 8 Fracture surface in impact tension of SiC_w/7475 composite

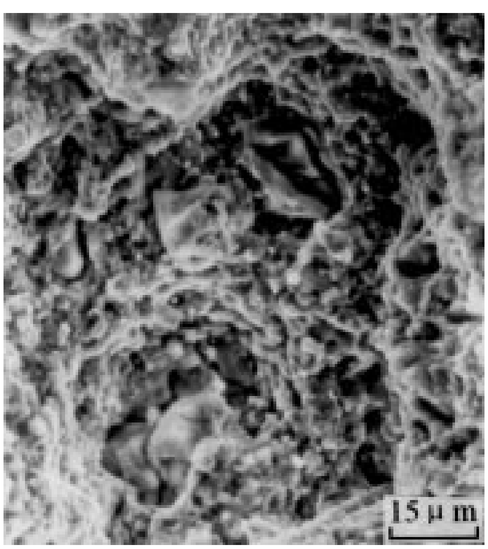


Fig. 9 Fracture surface in LCF of SiC_w/7475 composite

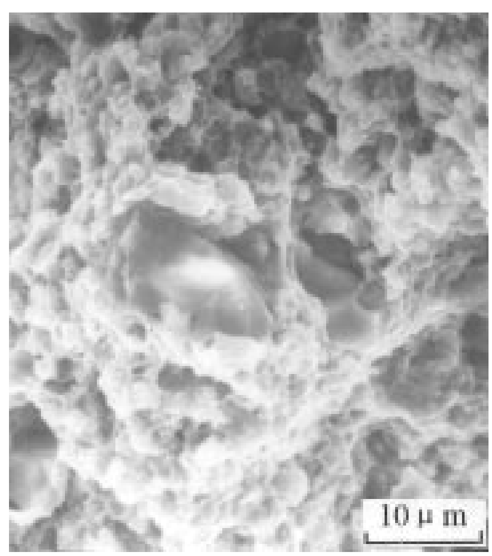


Fig. 10 Fracture surface in LCIF of SiC_w/7475 composite

pace with that of the matrix, therefore first, the unstable break occurred in whisker clumps, leading to a transient drop in the load. Secondly, through blunting of cracks tip and a continuous deformation hardening of the matrix, the load came up again. This gave rise to initiation and propagation of microcracks in other areas, resulting in the load drop again. The process continued repeatedly, and hence the load-displacement curve of sawtooth shape formed. On the fracture surfaces of impact tension specimens, the microscopic patterns were similar to those of static tension (Fig. 8).

In the fracture surface of LCF and LCIF the broken or debonded SiC particles often formed large cavities, around which there were ridges of dimples (Fig. 9, 10). Based on SEM analysis, it is considered that in SiC_w/7475 composite the fatigue cracks often initiate within SiC particles and along their interfaces and propagate by the cavity-coalescence mechanism. This confirms that the fatigue damage is sensitive to stress concentration in the micro area.

4. Conclusions

- In LCF of the SiC_w/7475, slight cyclic hardening occurred, while in LCIF, cyclic stability appeared.
- In single tension (static or impact) of the SiC_w/7475 composite, the first break occurs in whisker clumps, but in LCF and LCIF the cracks often initiate within or near the SiC particles that mingle in the composite.
- For a SiC_w/7475 composite the strain-rate effects on yield stress, ductility, cyclic hardening and softening, $\Delta\varepsilon_e/2 - N_f$ relation, and transition life were weak.
- For SiC_w/7475 and SiC_p/Ly12 composites, the impact tension strength, ductility, cyclic hardening and softening, and transition life are similar when their tensile strength is close.
- In the SiC_w/7475 composite, the ductility is much lower than that in the matrix alloy. In low cycle fatigue a brittleness appears, therefore, careful attention must be paid when the composite is used as a structural material.

Acknowledgments

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