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Microstructural characterization of a silicon carbide whisker reinforced 2124 aluminium metal matrix composite

P. K. LIAW, J. G. GREGGI, W. A. LOGSDON
Metallurgy Department, Westinghouse R&D Center, Pittsburgh, Pennsylvania, USA

The microstructure of a silicon carbide whisker (SiC_w) reinforced 2124 aluminium metal matrix composite was characterized using scanning transmission electron microscopy (STEM). The SiC whiskers ranged in length from approximately 2 to 10 μm, and demonstrated good bonding to the aluminium matrix. In a few cases, the interface between SiC whiskers and the aluminium matrix exhibited wavy characteristics. The size of subgrains in the aluminium matrix was found to be dependent upon that of SiC whiskers. In addition, two types of intermetallic compounds were observed in the composite.

1. Introduction

Over the past few years, both continuous and discontinuous metal matrix composites have become increasingly popular for structural applications because of their excellent strength to density and stiffness to density ratios. Many experts suggest, however, that the future of metal matrix composites will centre upon discontinuous fibres which are in the shape of chopped whiskers, particles or platelets [1–7]. In particular, silicon carbide whisker, particulate or platelet reinforced aluminium metal matrix composites are especially attractive because they can be shaped, machined and drilled by utilizing conventional metal fabrication facilities. Furthermore, composite materials are applicable to a variety of machined components and can be produced as rolled sheets, forgings and extrusions.

Our aims were basically twofold: (a) to develop a succinct, structural reliability prediction capability that can be easily applied by design engineers to structures manufactured from these metal matrix composites, and (b) to examine methods to improve the ductility, fracture toughness and fatigue crack growth resistance of metal matrix composites through a multiple disciplinary approach. Consequently, a program was initiated at this laboratory to characterize silicon carbide whisker and particulate reinforced aluminium metal matrix composites. Tensile, fracture toughness and fatigue crack growth rate (FCGR) tests were conducted at room temperature on 20 vol % SiC_w/2124 Al (T6), 25 vol % SiC_p/6061 Al [F (as-fabricated) and T6] and 25 vol % SiC_w/6061 Al (T6) metal matrix composites [5]. Generally speaking, the three metal matrix composites demonstrated increased yield and ultimate strengths, substantially inferior ductility and fracture toughness, a lower crack propagation resistance and essentially equivalent values of threshold stress intensity range, ΔK_{th}, compared with the corresponding wrought aluminium alloys.

The purpose of this paper is to present the results of a thorough microstructural characterization designed to examine the structure of the 20 vol % SiC_w/2124 Al (T6) metal matrix composite by using scanning transmission electron microscopy (STEM).

2. Experimental procedure

2.1. Material

The SiC_w/2124 Al was fabricated by DWA, Chatsworth, California, USA, and contained 22.45 wt % silicon carbide whiskers (grade F-9 type silicon carbide), which translates to approximately 20 vol %. This material was received as a relatively thin sheet (0.20 cm thick) and was subjected to a T6 heat treatment; that is, solution treated at 488 to 499° C in a salt bath for 10 min to 1 h, cold-water quenched, aged at 24° C for 48 h and then aged at 185 to 196° C for 11 to 13 h. The room temperature tensile and fracture toughness properties of this metal composite are summarized and compared with those of the conventional

TABLE I Tensile properties

Material	Orientation	0.2% Yield strength (MPa)	Ultimate strength (MPa)	Total elongation (%)
SiC_w/2124 Al (T6)	Transverse	390	476	1.3
SiC_w/2124 Al (T6)	Longitudinal	450	569	1.1
2124 Al (T851)*	–	393–462	455–496	5–10

*[8].

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TABLE II Fracture toughness

Material	ASTM E399 orientation	Fracture toughness (MPa $m^{1/2}$)
SiC_w/2124 Al (T6)	T–L	7.6
SiC_w/2124 Al (T6)	L–T	14.1
2124 AP (T851)*	–	26.6–38.4

*[8–13].

wrought 2124 aluminium alloy in Tables I and II, respectively. Note that the yield and ultimate strengths of the SiC_w/2124 Al (T6) metal matrix composite are slightly larger than those of the corresponding wrought aluminium alloy while the elongation of the composite is substantially smaller than that of the wrought material [5, 8]. Moreover, fracture toughness of the metal matrix composite was inferior to that of the wrought 2124 aluminium alloy [8–13].

2.2. Specimen preparation
For microstructural characterization, specimen preparation was started by mechanical thinning to a thickness of approximately 25 μm. Subsequently, ion-milling was conducted at a voltage of 5 kV and at an incidence angle of 15° to perforate thin specimens. The final ion-milling process experienced by the perforated specimens was accomplished at a voltage of 1.0 to 1.5 kV and at an incidence angle of 10° for 10 to 20 min. Ion-milling proved to be extremely effective in preparing STEM specimens of this aluminium metal matrix composite [14].

3. Results and discussion
Microstructural features of the SiC whisker reinforced 2124 aluminium metal matrix composite are presented in Fig. 1. The striated areas are SiC whiskers which have a length of approximately 2 to 10 μm. Previously, stacking faults and narrow twins of different thicknesses were found to represent the striated regions of SiC whiskers [6, 15]. The striated faults were attributed to the high deposition rates during the formation of SiC whiskers from rice hulls [16]. An amplified view of area A in Fig. 1a is presented in Fig. 1b. Small particle-like SiC whiskers of approximately 0.2 μm in size were observed. These subsized whiskers may result from "chopping up" of large whiskers during processing. The interface between the aluminium matrix and a SiC whisker is illustrated in Fig. 2. In Fig. 2a, a SiC whisker can be observed in the aluminium matrix; Fig. 2b is an amplified photograph of this interface. The SiC whisker exhibits a wavy boundary. The waviness of the SiC whisker is often called knottiness [17]. The knotted SiC whiskers have also been grown by a vapour–liquid–solid (VLS) process [17]. The characteristics of knottiness are typically associated with β-SiC whiskers [17]. The knottiness of SiC whiskers may serve as stress concentration notches and provide crack initiation sites, thereby degrading fracture properties of the composite [18]. In Fig. 2b, the bonding between the aluminium matrix and the SiC whisker appears good. In numerous cases, the SiC whiskers demonstrated relatively smooth boundaries, see Fig. 2c. Smooth boundaries were found to be characteristic of α-SiC whiskers [17].

The microstructure of the aluminium matrix and SiC whiskers is presented in Fig. 3. Subgrains of approximately 0.5 to 2 μm form in the aluminium matrix. Numerous dislocations were observed inside the subgrains. The presence of dislocations may be caused either by the deformation during the extruding process of the composite or by the great mismatch in the thermal expansion coefficients between SiC whiskers and the aluminium matrix [16]. Careful examination revealed that subgrains surrounded the SiC whiskers. Furthermore, the size of the subgrains was found to be dependent upon that of the SiC whiskers; that is, smaller subgrains accompany smaller SiC whiskers. Similar behaviour was reported in a SiC particulate (SiC_p) reinforced 6061 aluminium metal matrix composite [15].

Recall that the yield and ultimate strengths of the

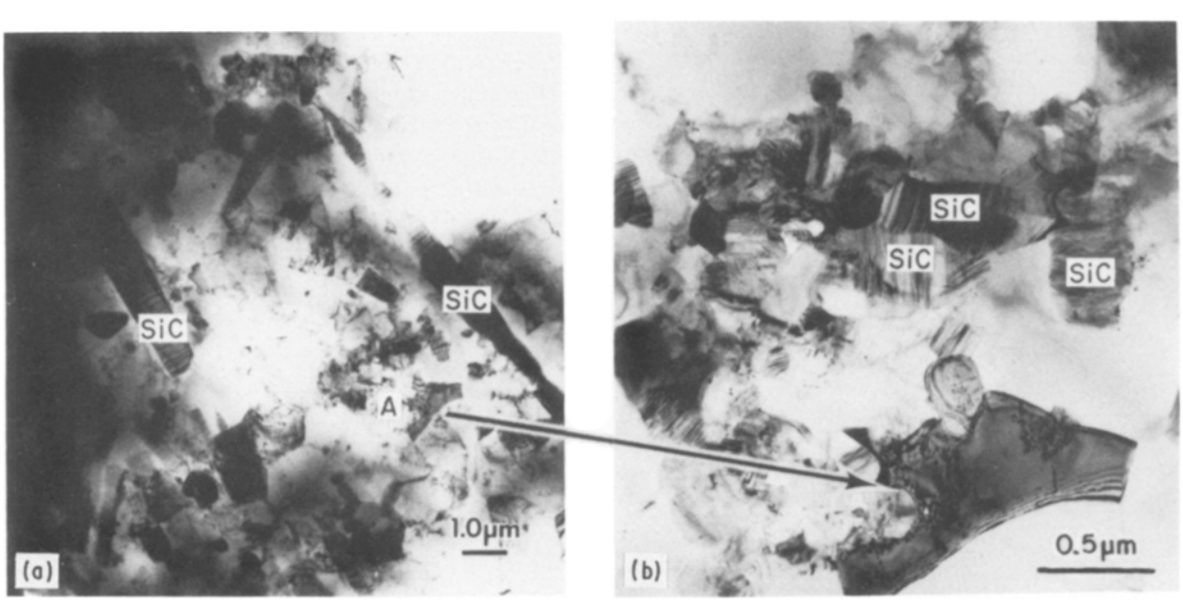

Figure 1 Distribution of silicon carbides (SiC). (a) Microstructure of SiC_w/2124 AP; (b) Enlargement of area A in Fig. 1a.

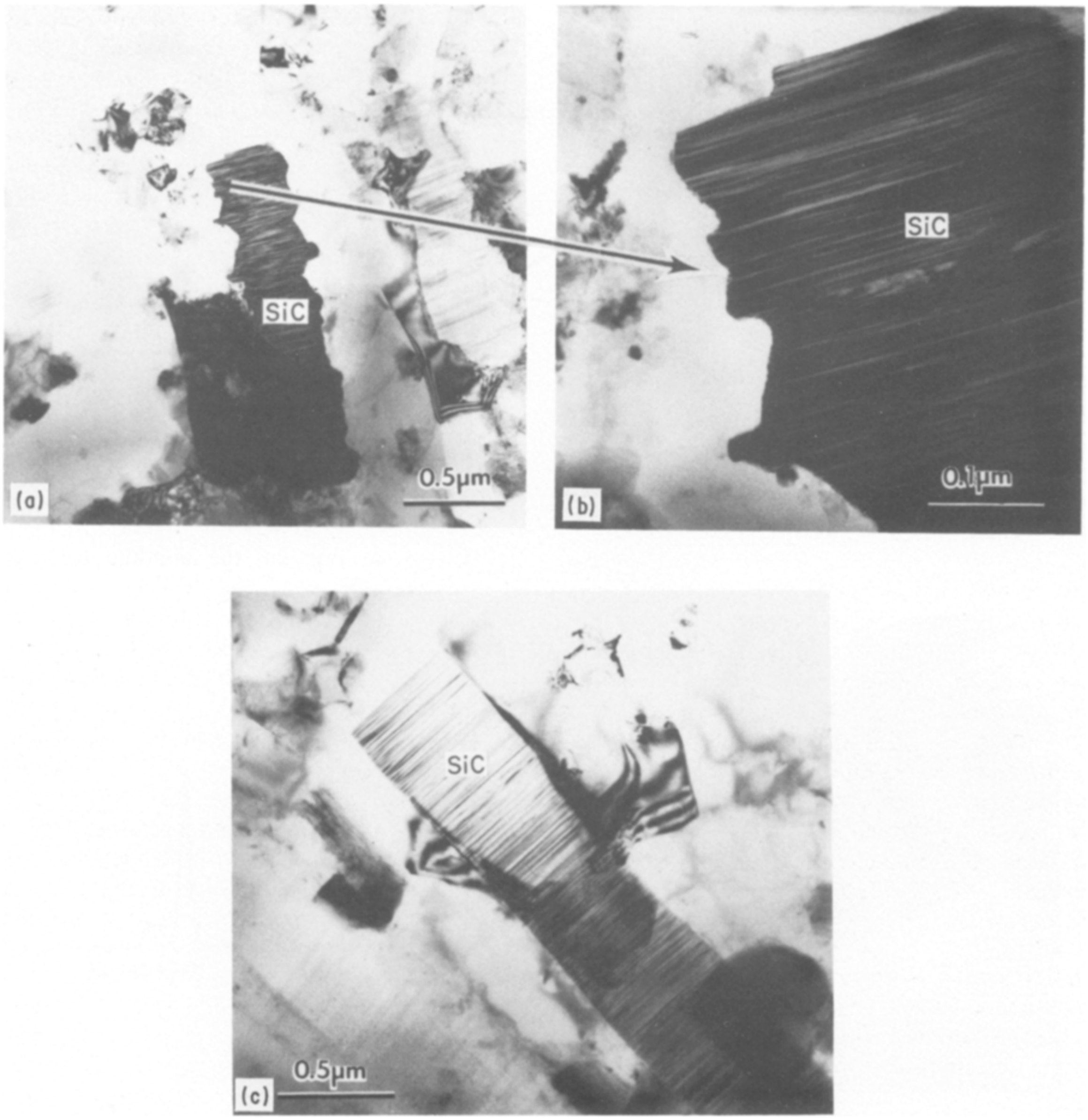

Figure 2 Interface between aluminium matrix and SiC. (a) SiC Whisker in aluminium matrix; (b) enlargement of Fig. 2a; (c) relatively smooth boundaries of SiC whiskers.

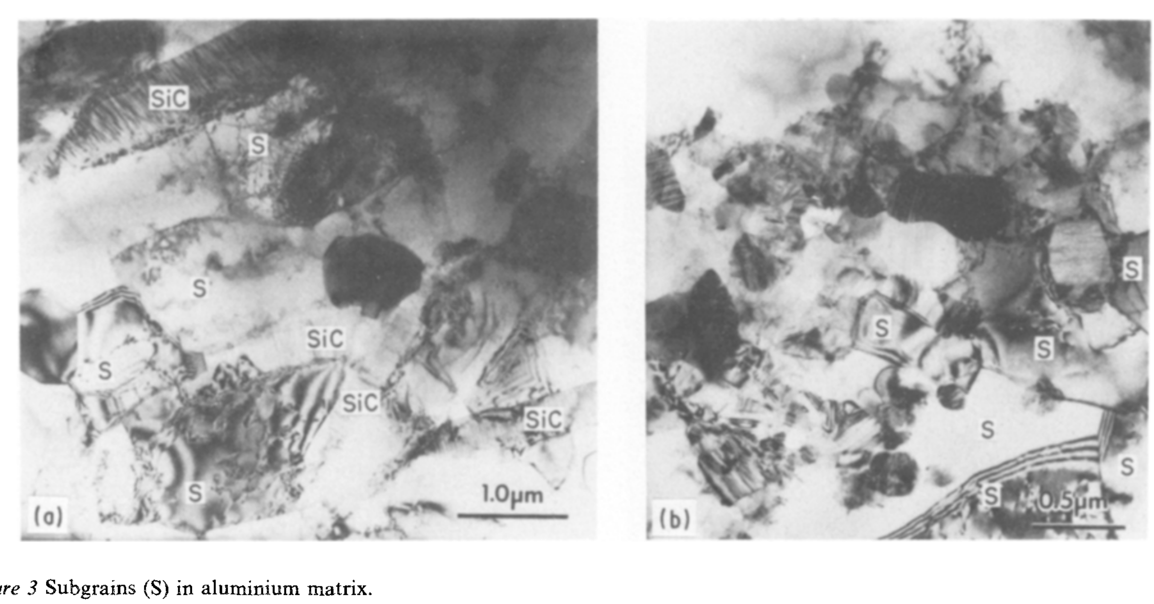

Figure 3 Subgrains (S) in aluminium matrix.

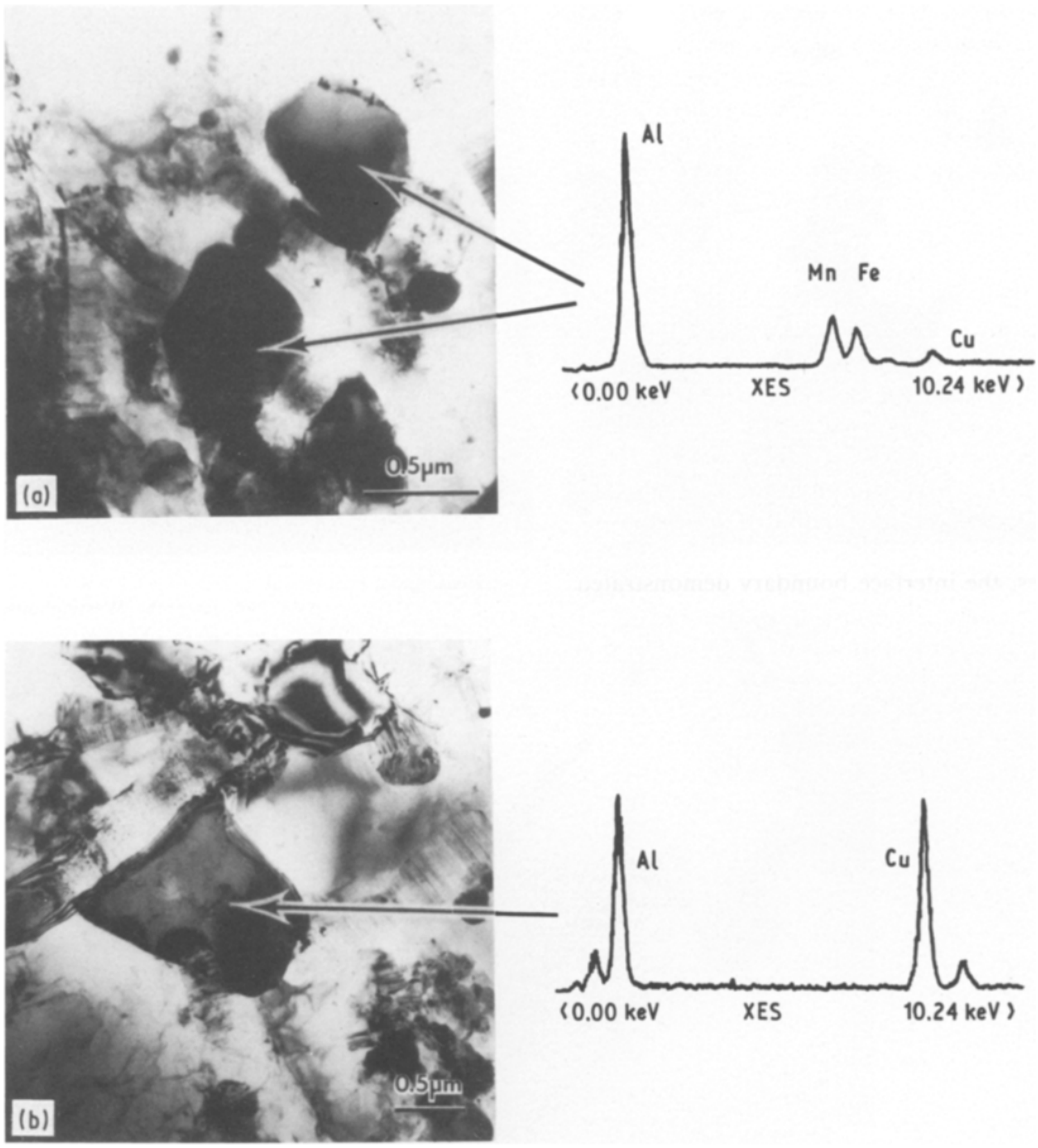

Figure 4 Identification of intermetallic compounds.

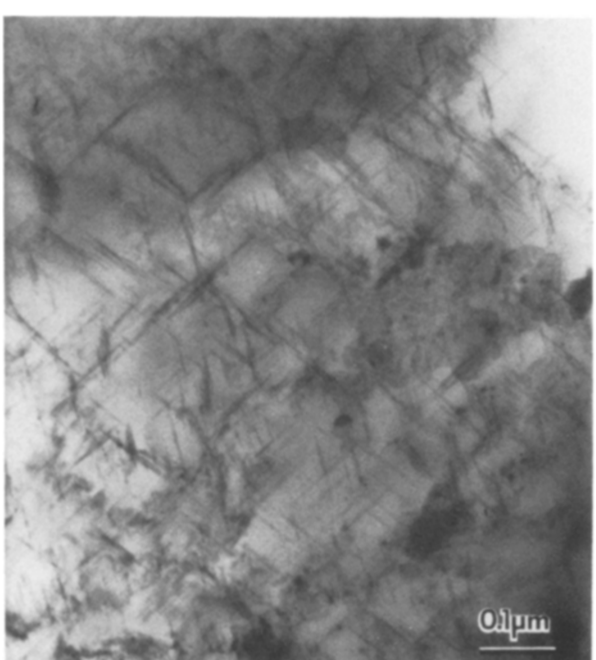

Figure 5 Precipitate phase of 2124 aluminium matrix.

SiC_w/2124 Al (T6) metal matrix composite were slightly larger than those of the corresponding wrought aluminium alloy. It has been suggested that, besides SiC whiskers, the strength level of the composite is also derived from the presence of subgrains and dislocations, as shown in Fig. 3 [15, 19, 20].

Intermetallic compounds within the composite are illustrated in Fig. 4. Two kinds of compounds were identified by using energy dispersive spectroscopy (EDS) of STEM. One compound mainly consisted of aluminium, manganese, iron and copper while the other was aluminium and copper. The intermetallic compounds formed during fabrication of the composite. These compounds were potentially detrimental to fracture properties [18].

The precipitate phase of the 2124 aluminium matrix is shown in Fig. 5. The plate-like precipitates were identified as $CuMgAl_2$ (S′ phase) characteristic of the age-hardening precipitates of the 2124 aluminium alloy [21]. Certainly, the precipitate phase in the aluminium matrix (Fig. 5) additionally strengthens the composite. Interestingly, using high resolution electron microscopy, MgO precipitates were observed in the interface between the aluminium matrix and the SiC whiskers [21]. Nutt and Carpenter suggested that the inferior fracture toughness typically displayed by a SiC reinforced aluminium metal matrix composite compared with the corresponding wrought aluminium alloy might be related to the presence of MgO precipitates [21].

4. Conclusions

The microstructure of a silicon carbide (SiC) whisker reinforced 2124 aluminium metal matrix composite was characterized by using scanning transmission electron microscopy. The length of the SiC whiskers ranged from approximately 2 to 10 μm although sub-sized SiC whiskers were also observed. The interface boundary between the aluminium matrix and SiC whiskers was found to be relatively straight although, in a few cases, the interface boundary demonstrated wavy characteristics. The size of subgrains in the aluminium matrix was found to be dependent upon that of SiC whiskers. Two kinds of intermetallic compounds were identified. The first intermetallic compound consisted of aluminium, manganese, iron and copper while the second type was simply aluminium and copper.

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