JOURNAL OF MATERIALS SCIENCE 29 (1994) 3767–3773

The structure and tensile properties of Al–Si alloy hybrid reinforced with alumina–aluminosilicate short fibre

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Alumina–aluminosilicate fibre hybrid reinforced aluminium–silicon alloy was fabricated by pressure infiltration route. Tensile test results at room temperature and at 300 °C are reported. It is shown that the alumina–aluminosilicate fibre ratio does have a strong influence on the ultimate tensile strength (UTS) of these hybrid composites. At an alumina–aluminosilicate ratio of 3:2, the optimum UTS of hybrid metal matrix composites (MMC) was obtained. The UTS of only alumina fibre reinforced MMC was improved with increasing fibre volume fraction at 300 °C. No fibre put-out was observed on the fracture surface and longitudinal section.

1. Introduction

Metal matrix composites (MMC) have been receiving significant attention in recent years. In many instances the properties of a reinforced metal have been shown to provide a performance advantage over monolithic metal, but the high cost of the composite has prohibited widespread commercial use [1–3]. Of the many potential metal matrix systems, aluminium alloy matrix composites have been the object of much research. Primarily due to the light weight, low cost and ease of fabrication of aluminium. Within the class of aluminium alloy matrix composites, the discontinuous reinforced MMCs are very important, particularly in the area of potential automotive application [4–6]. So far, one of the most successful applications is the alumina short fibre reinforced aluminium alloy matrix piston. But, there is still much work to do and many barriers to conquer before widespread application can be expected. These challenges include such issue as costs, processing for specific properties etc. [7–10].

The present paper discusses the possibility of inexpensive aluminosilicate fibre replacement for alumina fibre for the production of an Al–Si alloy matrix composite, which is expected to be used for manufacturing automotive pistons. The price of alumina is more than 20 times that of aluminosilicate fibre. Via the use of the pressurized liquid–metal infiltration technique, the composite was fabricated. Herein, the tensile behaviour at ambient and elevated temperatures was examined; the effect of alumina–aluminosilicate fibre ratios on the properties of the composite are described. In addition, comparisons are made between characteristics of the present composite reinforced with only alumina fibre, and the existing composite described in the literature.

2. Experimental procedure

For fabrication of alumina–Al and alumina–aluminosilicate–Al composite materials, an Al–Si alloy was used as a matrix. The chemical composition of matrix is (wt %): 12.0% Si, 0.8% Cu, 1.0% Mg, 1.0% Ni, which is similar to SAE321. Alumina fibre and aluminosilicate fibre were obtained from China Louyang Refractory Materials Co. Specifications of the alumina and aluminosilicate fibres are shown in Table I.

The composites were fabricated by squeeze infiltration of liquid metal. The technique of liquid metal infiltration requires a porous preform which consists of the fibres. The method used to prepare preforms is as following: dispersion of the fibres in water in the presence of a phosphoric acid colloid; which acts as a binder; subjecting the dispersions to filtration under air pressure to produce a preform; and, then drying in air at about 200 °C and sintering at about 800 °C. The phosphic acid colloid content was 2–4 wt % of the preform. The alumina–aluminosilicate fibre ratios were shown in Table II. Preforms consisting of only alumina fibres were also prepared for comparison with the hybrid material, and for investigating the effect of total volume fraction on the mechanical properties.

Prior to being made into a preform, both alumina and aluminosilicate fibres were pretreated in order to obtain homogeneous dispersed fibres and to eliminate harmful impurities, such as slags etc. Fig. 1a, b shows photomicrographs of alumina and aluminosilicate fibres from the raw materials before pretreatment respectively. Fig. 1c, d is a photograph taken after pretreatment. Fig. 1 indicates that the fibres after pretreatment were cleaner and easier to disperse than the raw materials.

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TABLE I Specification of alumina and aluminosilicate fibres [11]

Material	Composition (wt %)	Diameter (μm)	Length (μm)	Aspect ratio (L/D)	Tensile strength (GPa)
Alumina	Al_2O_3:85–88 SiO_2:12–15	6–10 Av = 8	40–300 Av = 180	5–30 20	1.8 ~ 2.0
Aluminosilicate	Al_2O_3:60–62 SiO_2:38–40	1–3 Av = 2	20–100 Av = 65	20–15 30	1.0 ~ 1.2

TABLE II Alumina–aluminosilicate fibre ratios in hybrid preforms

Preform no.	V_1[a] (%)	V_2[b] (%)	$V_1:V_2$ ratio
1	12.0	0.0	12:0
2	7.2	4.8	3:2
3	4.8	7.2	2:3
4	2.4	9.6	1:4
5	0.0	12.0	0:12

The metal matrix composites were fabricated by the direct squeeze infiltration route. A 200 ton hydraulic press and cylindrical mould were used. Aluminium–silicon alloy was heated to 720 ± 10 °C, and the preform was preheated to ± 750 °C. The applied pressure was 150 MPa, and the ram speed was 0.90 m s^{-1}. During solidification, the pressure was maintained for 15–20 s, and the alloy was then water quenched.

To check the distribution of reinforcements, MMCs microstructures were observed through the optical microscope. Hardness test were performed with a Rockwell hardness number testing machine (B scale). Round tensile specimens, with 5 mm diameter and 30 mm gauge length, were machined from the cast composites. Ambient temperature tensile tests were performed using an hydraulic mechanical test system. Elevated temperature tensile tests were carried out with an LJ–500 test system at 300 °C. Ductility was determined by drawing two parallel lines, marking the gauge length on the specimen, and measuring the distance between the lines before and after tensile testing, using calipers. All the specimens were heat

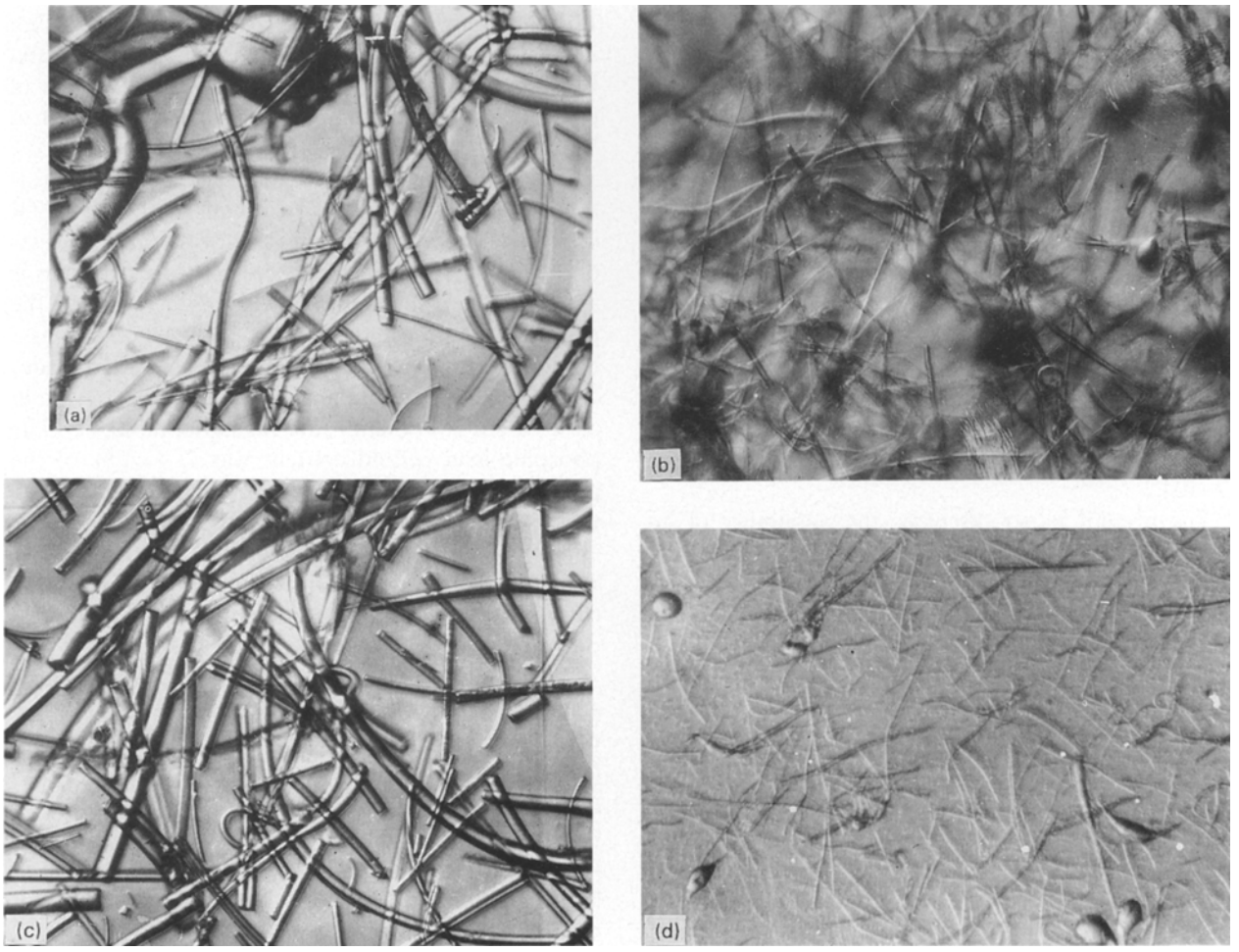

Figure 1 Optical micrographs of fibres prior to being made into a preform. (a) alumina fibres before pretreatment, × 200; (b) aluminosilicate fibres before pretreatment, × 200; (c) alumina fibres after pretreatment, × 200, and (d) aluminosilicate fibres after pretreatment, × 200.

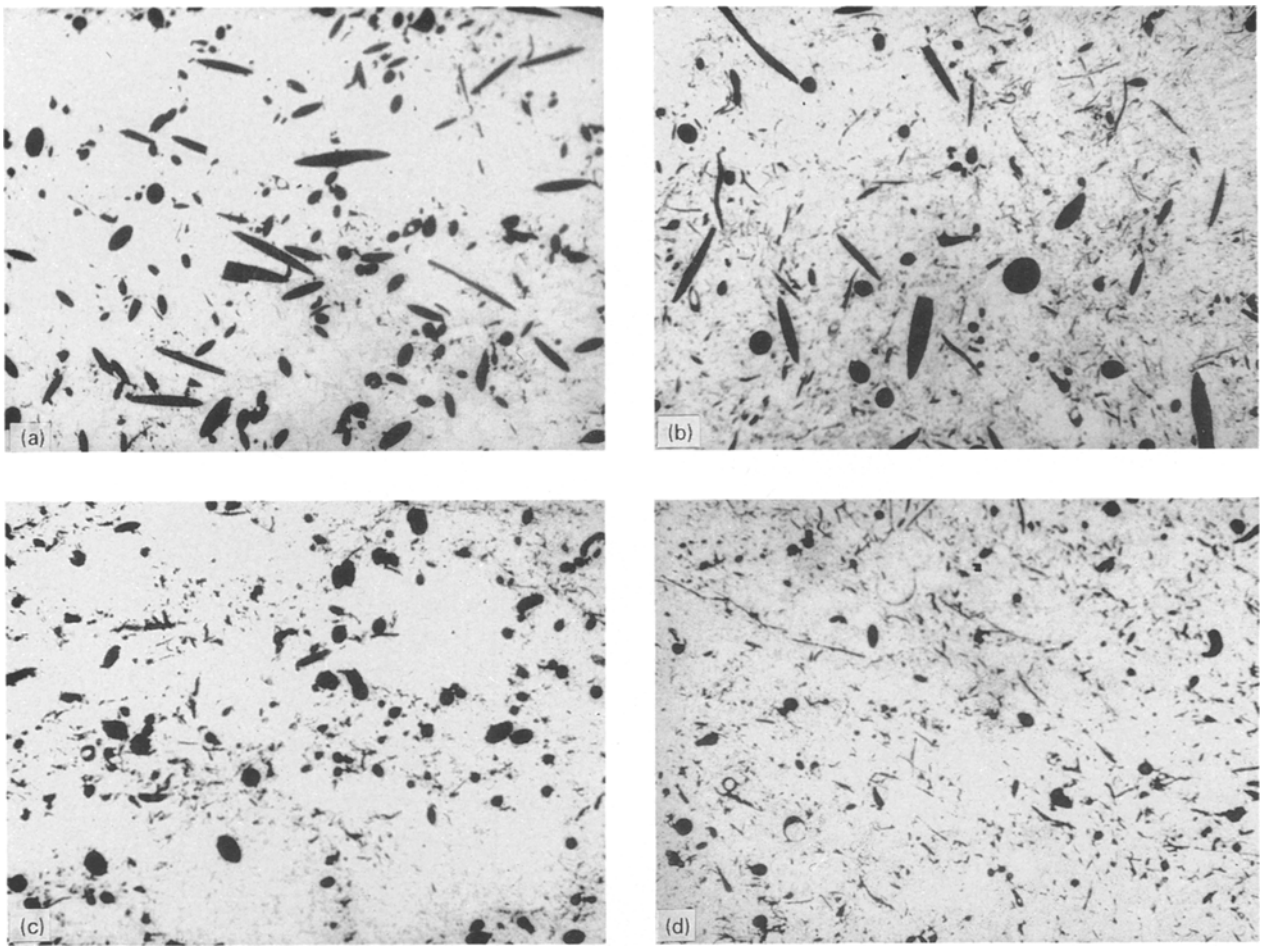

Figure 2 Optical micrographs of hybrid composites, × 100; (a) $V_1 = 0.12$, $V_2 = 0$; (b) $V_1 = 0.072$, $V_2 = 0.048$; (c) $V_1 = 0.096$, $V_2 = 0.024$; and (d) $V_1 = 0$, $V_2 = 0.12$.

treated under T_6 conditions, and were machined perpendicular to the direction of applied pressure. After tensile testing, the fracture surface at room and elevated temperature was examined by scanning electron microscopy (SEM) and optical microscopy.

3. Results

3.1. Structure

Four optical micrographs, Fig. 2, show that the alumina and aluminosilicate fibres are well dispersed in the aluminium alloy matrix. These composites were all infiltrated with no signs of residual porosity, and exhibited a two-dimensional random distribution of both alumina and aluminosilicate fibres. No severe damage of reinforcements caused by the high applied pressure was found.

3.2. Mechanical properties at room temperature

The effect of the alumina–aluminosilicate fibre ratio on hardness of hybrid composites was illustrated in Fig. 3. At an alumina–aluminosilicate ratio of 3:2, i.e. alumina fibres $V_1 = 7.2\%$, aluminosilicate fibres $V_2 = 4.8\%$, the maximum hardness of hybrid MMC was obtained; the hardness of all the MMCs is higher than that of the unreinforced alloy.

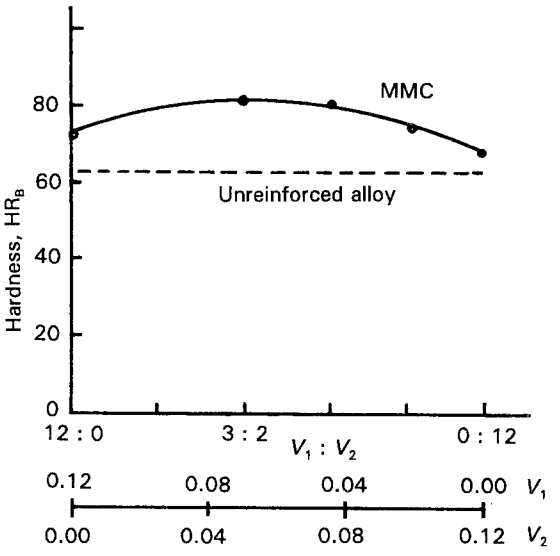

Figure 3 The effect of alumina–aluminosilicate fibre ratio on the hardness of hybrid MMC.

Tensile tests at room temperature showed that the ultimate tensile strength (UTS) of all the composites was lower than that of the unreinforced aluminium–silicon alloy, as shown in Figs 4 and 5. In detail, the UTS of hybrid composites varied with the alumina–aluminosilicate fibre ratio; this is similar to the hardness case. Fig. 5 showed the effect of the

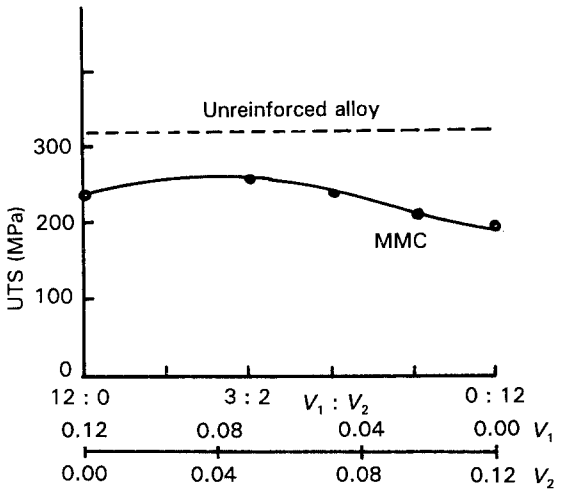

Figure 4 The effect of alumina–aluminosilicate fibre ratio on UTS of hybrid MMC at room temperature.

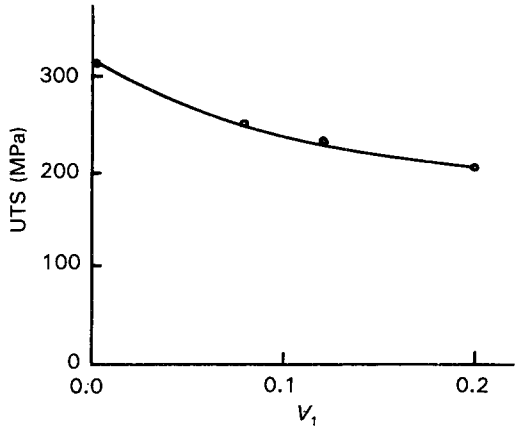

Figure 5 Variation of UTS with the volume fraction of alumina fibres at room temperature.

volume fraction of reinforcements on the UTS of composites reinforced with alumina fibres only. It is clear from Fig. 5 that the UTS decreased as the volume fraction of alumina increased. This indicates that there is no improvement in composite strength with alumina or aluminosilicate fibres at room temperature. Ductility of all the MMCs is lower, about 1.0–1.5%, similar to the unreinforced Al–Si alloy.

3.3. Mechanical properties at elevated temperature

Tensile tests at 300 °C showed that the UTS, of the composites reinforced only with alumina fibres, increased with increasing volume fraction of reinforcement, as shown in Fig. 6. At $V_f = 12\%$, the UTS of MMC responded to 145 MPa, which was 40% higher than that of the unreinforced Al–Si alloy. This result is similar to the data in Reference [12], which is also plotted in Fig. 6.

Figs 7 and 8 show the variation of UTS and ductility of hybrid composites with the alumina–aluminosilicate fibre ratio at 300 °C. The UTS of all the hybrid MMCs was higher than that of the unreinforced Al–Si alloy. Particularly, at the ratio of 3:2, i.e. $V_1 = 7.2\%$, $V_2 = 4.8\%$, the optimum UTS was

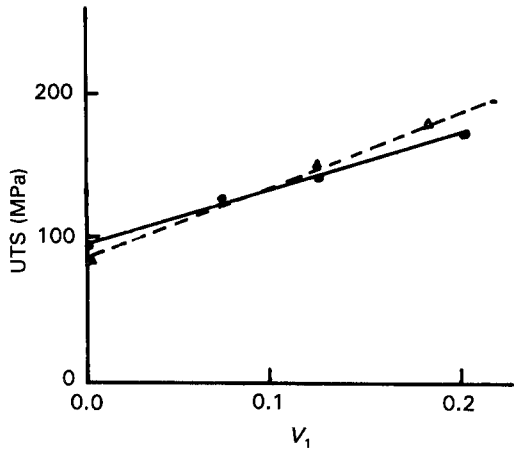

Figure 6 Comparison of UTS of Composites from (●) this work, and (▲) Weeton *et al.* [12].

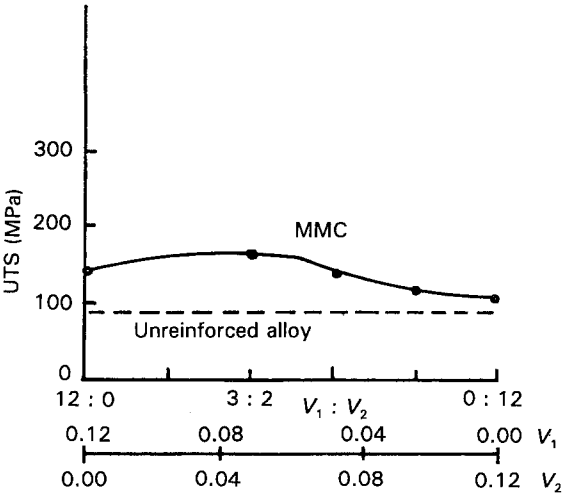

Figure 7 The effect of alumina–aluminosilicate fibre ratio on the UTS of hybrid MMC at 300 °C.

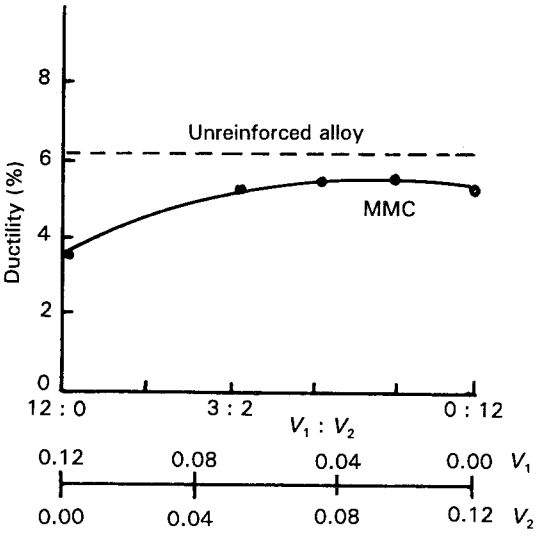

Figure 8 The effect of alumina–aluminosilicate fibre ratio on the ductility of hybrid MMC at 300 °C.

obtained, which was equal to about 162 MPa. The UTS was increased by 70, 16 and 58% compared to the corresponding values for $V_1 = V_2 = 0\%$; $V_1 = 12\%$, $V_2 = 0\%$; and $V_1 = 0\%$; $V_2 = 12\%$, respectively.

But, if the alumina–aluminosilicate fibre ratio was less than 3:2, the UTS of hybrid composites decreased, evidently with decreasing ratio. The UTS of composites reinforced only with aluminosilicate fibres, i.e. $V_1 = 0$, $V_2 = 12\%$, was only 10% higher than that of the unreinforced Al–Si alloy. In addition, it is very interesting that ductility of the hybrid composites was also superior to that of the composites reinforced only with alumina or aluminosilicate fibres, as shown in Fig. 8. Thus, it is necessary to control the alumina–aluminosilicate fibre ratio in order to achieve superior mechanical properties; it is possible that the alumina fibres are partly replaced by inexpensive aluminosilicate fibres.

3.4. Fractographic study

Fig. 9a, b shows the fracture surface of tensile specimens at 300 °C and room temperature, respectively. Dimples was observed most clearly in Fig. 9a for a total volume fraction of 12%, indicating localized ductility for the composites at elevated temperatures, i.e. 300 °C. But, the micrograph of the room temperature fracture surface of hybrid composites shows the characters of brittle fracture. No fibre pull-out was observed in any of these composites. The fracture surface was also identified in longitudinal section optical micrographs of the tensile specimens both at elevated and room temperature, as shown in Fig. 10. This indicates that the fibre/–/metal interface was strongly bonded. Furthermore, Fig. 11a shows the longitudinal section area, which is 10 mm away from the fracture surface, after tensile testing at 300 °C. It is observed that most of the fibres were broken after tensile testing at elevated temperature. But in contrast, no broken fibres were observed in any of these composite after tensile testing at room temperature, as shown in Fig. 11b. This points out that short fibres did

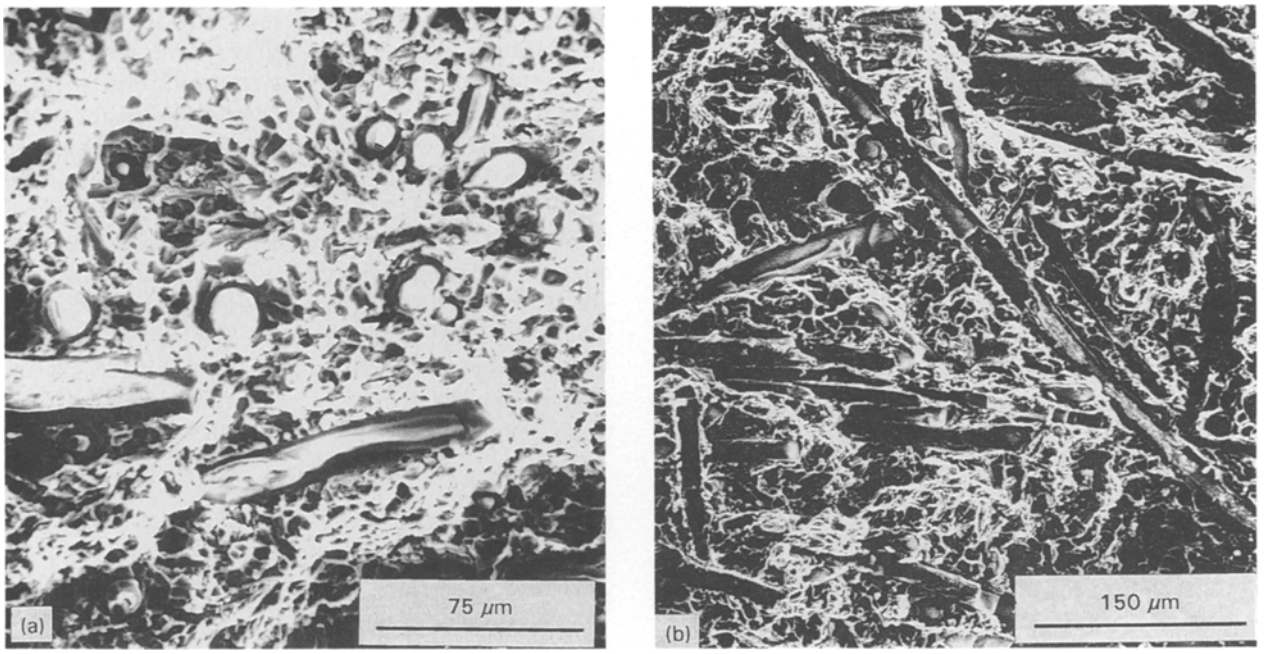

Figure 9 Scanning electron micrographs of the fracture surface of composites: (a) at 300 °C, $V_1 = 0.072$, $V_2 = 0.048$; and (b) at room temperature, $V_1 = 0.12$, $V_2 = 0$.

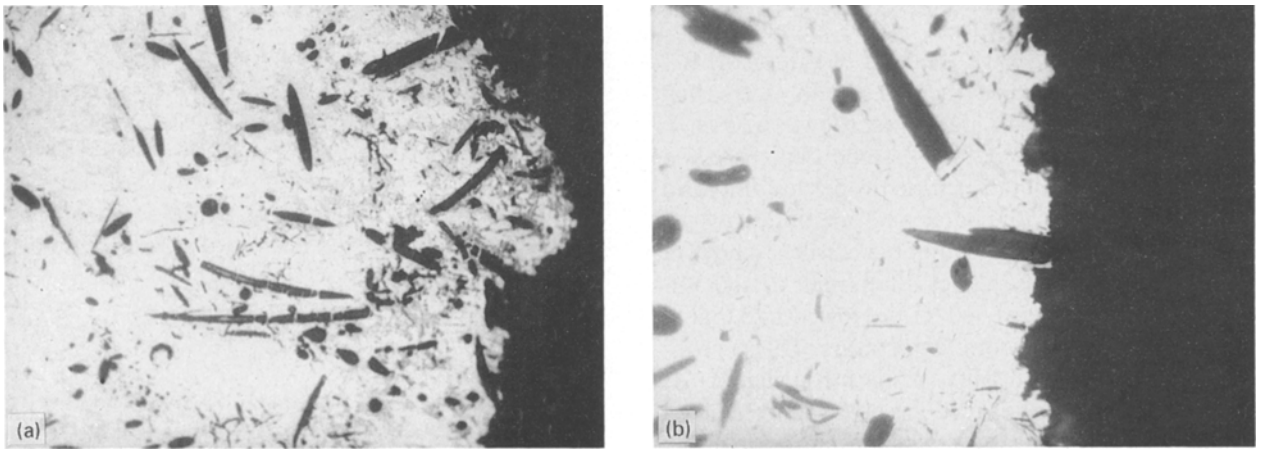

Figure 10 Longitudinal section micrographs of the fracture surface of composites: (a) at 300 °C, $V_1 = 0.12$, $V_2 = 0$, × 100; and (b) at room temperature, $V_1 = 0.048$, $V_2 = 0.072$, × 200.

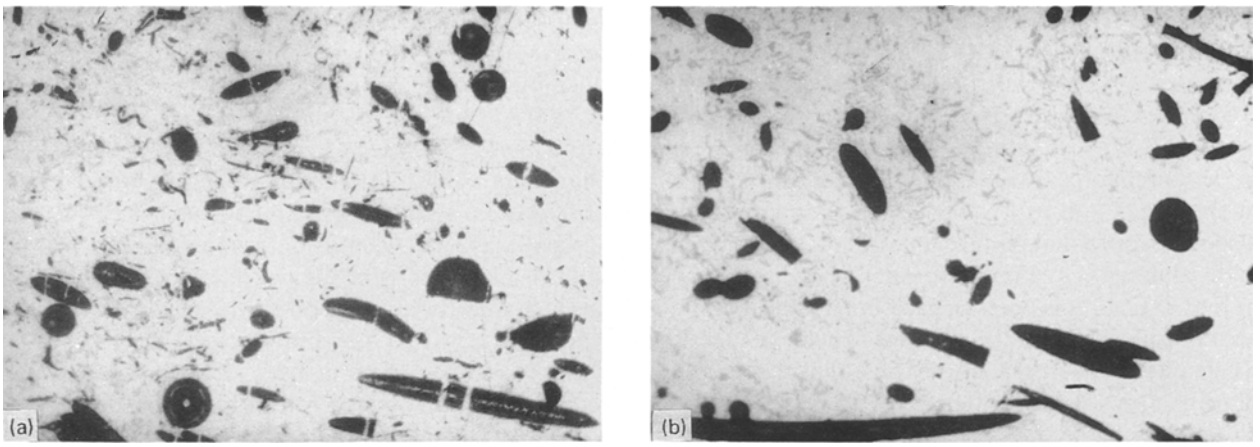

Figure 11 Optical longitudinal section micrographs, which is 10 mm away from the fracture surface of hybrid composites: (a) at 300 °C, $V_1 = 0.048$, $V_2 = 0.072$, ×200; and (b) at room temperature, $V_1 = 12\%$, $V_2 = 0$, ×200.

play a very important role in enhancing the tensile properties of MMCs at elevated temperature, but deterioration of the tensile properties of MMCs at room temperature.

4. Discussion

The results presented above show that it is possible to produce alumina–aluminosilicate fibre hybrid MMC components by the preform infiltration route. At an alumina–aluminosilicate fibre ratio of 3:2, the optimum ultimate tensile properties of hybrid composite were obtained both at room and elevated temperature. This may be related to the difference in physical and mechanical properties of the two reinforcements, as listed in Table I. The diameter, length and tensile properties of alumina fibres are much greater than that of aluminosilicate fibres. If the alumina–aluminosilicate fibre ratio is higher than 3:2, the skeleton of the preform is mainly bridged by coarse alumina fibres, whereas the fine aluminosilicate fibres are dispersed among the suspension of the alumina fibre skeleton. This kind of preform structure elaborates the fully reinforcing effect of both coarse alumina and fine aluminosilicate fibres themselves. If the alumina–aluminosilicate fibre ratio is less than 3:2, the skeleton of preform is mainly bridged by fine aluminosilicate fibres, whereas the coarse alumina fibres are dispersed and laid in the aluminosilicate fibre skeleton. In this case, the UTS of hybrid MMCs at elevated temperature increases with decreasing alumina–aluminosilicate ratio, as shown in Fig. 7. Therefore, in general, authors assume that there is a ratio to achieve optimum tensile properties of hybrid MMCs reinforced with coarse and fine fibres.

In the present work, the ultimate tensile strength of all the composites is higher than that of the unreinforced Al–Si alloy at 300 °C, but lower than that of unreinforced alloy at room temperature. This is probably related to the ductility of the metal matrix. At room temperature, the ductility of the unreinforced Al–Si alloy is very low, the stress concentration at the reinforcement fibre end could not be relaxed, and brought about decohesion of fibres from the matrix. These voids could propagate quickly toward the matrix, and lead to brittle fracture of the MMC. In fact, the fibres did not reinforce the matrix at room temperature, as shown in Figs 4 and 5. But, at elevated temperature, 300 °C, the ductility of the matrix was evidently improved; the stress concentration at fibre ends could be relaxed by the annihilated dislocation, recrystallization of the matrix, and grain boundary migration [13, 14]. The stress at the fibre ends was equal to zero [15]. Thus, the matrix stress could be transmitted to the reinforcements by a fibre–matrix interface shearing action. Finally, fibre breaking results in the fracture of the composite, which indicates that the fibre did reinforce the Al–Si matrix at elevated temperatures, as shown in Figs 6, 7 and 11. Such an analysis implies that fibre reinforcing effects of the matrix depend on the ductility of the matrix.

5. Conclusions

1. Alumina–aluminosilicate hybrid MMCs can be produced by the preform infiltration route.
2. The ultimate tensile strength (UTS) of all the MMCs in the present work is higher than that of the unreinforced Al–Si alloy at 300 °C, but lower than that of the unreinforced alloy at room temperature.
3. An alumina–aluminosilicate fibre ratio of 3:2, the optimum ultimate tensile properties of hybrid MMC was obtained at 300 °C. The UTS was equal to 162 MPa, which was 70, 16 and 58% higher than that of the unreinforced alloy, MMCs reinforced only with alumina fibres and with aluminosilicate fibres only, respectively.
4. The UTS of MMCs reinforced only with alumina fibre increased with the increasing total volume fraction of fibres at 300 °C, but decreased at room temperature.

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Received 13 May
and accepted 16 December 1993