# High-temperature strengths of aluminium composite reinforced with continuous SiC fibre

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Aluminium alloys were reinforced unidirectionally with 30, 35, 40 and 50 vol % SiC fibres by a liquid-pressing method. The SiC fibres for reinforcement were produced from a polycarbosilane and were "yarns" consisting of 500 continuous filaments of length 300 m and diameter 13 μm, having a tensile strength of 2000 MPa. High-temperature tensile and bending strengths of the composites were examined in air in the temperature range from room temperature to 500° C. The strengths were not influenced by temperature up to 400° C, but were decreased at 500° C. The decrease is considered to be caused by the reduction in transfer efficiency of the stress accompanying the decrease in adhesion between fibres and matrix.

## 1. Introduction

In recent years, fibre-reinforced metal composites have attracted attention as heat resisting the high specific strength materials. Metal reinforced by graphite fibre, aluminium oxide fibre (Fibre FP) or SiC fibre have been vigorously studied.

Pfeifer and Kinna [1] report that available graphite-fibre reinforced aluminium alloy composites are materials with good mechanical properties both at room and elevated temperatures, Champion *et al.* [2] report that Fibre FP, developed by Du-Pont is an excellent fibre for the reinforcement of metal composites. SiC fibres are also considered to be promising for reinforcement of metal composites, as well as graphite fibres and Fibre FP.

Long, continuous SiC fibres are of two types. One fibre is a SiC monofilament (140 μm in diameter) made by a controlled vapour deposition (CVD) method with carbon filament as the core. This SiC filament is now being produced in pilot plant quantities by the AVCO Systems Division, Lowell, Mass. Metal composites reinforced using this filament have been studied by Webster [3], and it is reported that filament–matrix bonding in SiC monofilament reinforced aluminium composite is poor. The other fibre is a coreless, continuous SiC multifilament (13 μm in diameter) produced by heating melt-spun polycarbosilane. This fibre was developed by Yajima and co-workers, and has high tensile strength, high Young's modulus and good oxidation resistance [4, 5]. This SiC fibre is extremely fine and flexible. In making metal composites of complex shape, therefore, the SiC fibre is considered to be superior to the SiC monofilament. Kasai *et al.* [6, 7] have studied aluminium composites unidirectionally reinforced using SiC fibre of length 600 mm and a tow of 4000 to 5000 fibres. A pilot plant to produce the SiC fibre used by them is at an early stage of development. They report that the SiC fibre is easily compatible with metals and is promising for the reinforcement of metal composites.

The SiC fibre developed by Yajima and co-

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workers is now being manufactured in a pilot plant as "Nicalon"*, with lengths between 300 m and 500 m, and yarns of 500 continuous filaments, by Nippon Carbon Company Ltd. In this paper, this continuous fibre is referred as SiC fibre. The present authors have studied the metal–matrix composite reinforced with SiC fibre, where aluminium was used as the metal. A 6061–Al composite reinforced unidirectionally with SiC fibre by a liquid-pressing method has been produced and it was reported that the tensile strength obeyed the rule of mixtures (ROM) up to a fibre volume-fraction of 38% [8].

The tensile and bending strengths of the aluminium composites reinforced with continuous SiC fibres have been studied at high temperatures and it is these results that are described in this work.

## 2. Experimental procedure

### 2.1. Preparation of the SiC fibre-reinforced aluminium composites

"Nicalon"* SiC fibres were used as the reinforcement; "yarns" were used composed of 500 filaments, each 13 $\mu$m in diameter. The fibre properties are: tensile strength 2000 MPa, tensile modulus 200 GPa and density 2.55 g cm$^{-3}$. For the Al matrix, 1100–Al and 6061–Al sheets of length 120 mm, width 70 mm and thickness 0.3 mm were used. The aluminium composite reinforced unidirectionally with SiC fibres (SiC fibre–Al) was produced by a liquid-pressing method, as follows [8]. SiC fibre yarns were wound around a drum of diameter 300 mm and width 300 mm and bonded together with polystyrene. A sheet of SiC fibre, of length 940 mm and width 300 mm was prepared by the above method. It was then cut into sheet pieces of length 120 mm and width 70 mm. These sheet pieces were stacked up alternately with the aluminium sheets in a stainless steel vessel and then the vessel with the laminate was heated up to 720° C in a vacuum. The heated vessel was immediately pressed, as in Fig. 1, and The SiC fibre–Al composite was thus produced.

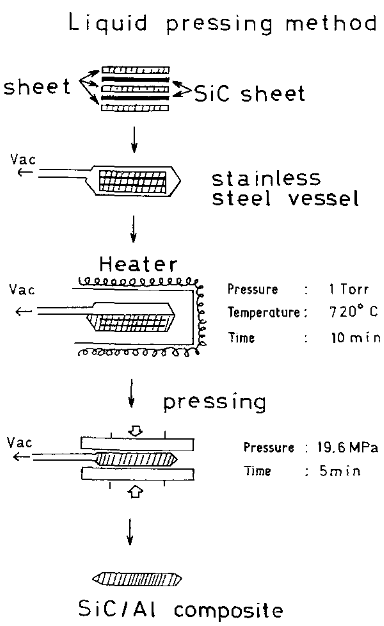


*Figure 1* Preparation by a liquid-pressing method of aluminium composite reinforced with SiC fibres.

### 2.2. Testing method

A Shimadzu-Auto Graph-IS-5000 machine was used for both longitudinal tensile and bending tests of the composite specimens (of up to 35 mm in length) heated uniformly to high temperatures in air. For each temperature at which measurements were taken, five composite specimens were tested. The configuration of the tensile test specimen is shown in Fig. 2. The specimens were held in the chuck by pins to prevent slippage at high temperature. The dimensions of the bending test specimens were 40 mm x 10 mm x 2 mm. Tensile tests were performed with a gauge length of 35 mm and a cross-head speed of 1 mm min$^{-1}$; the three-point bending tests were performed with a span of 30 mm and a cross-head speed of 1 mm min$^{-1}$. Both the strengths were measured in air in the temperature range from room temperature to 500° C; measurements were taken after allowing the specimen to remain at the chosen temperature for 15 min.

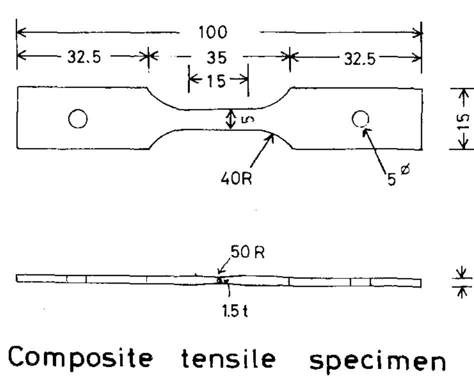


*Figure 2* Composite tensile specimen configuration (dimensions in mm).

*"Nicalon" is a registered trade mark of the Nippon Carbon Company, Ltd.

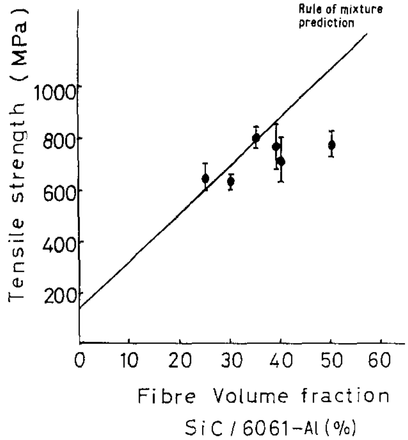


*Figure 3* Tensile strength of SiC fibre–Al plotted against fibre volume-fraction.

## 3. Results and discussion

Fig. 3 shows the relationship between the SiC fibre volume-fraction, $V_f$, and the tensile strength at room temperature for the SiC fibre/6061–Al composites, prepared by the procedure shown in Fig. 1. The line in Fig. 3 shows the prediction from the rule of mixtures (ROM). The values at $V_f = 25$, 38, 40 and 50% are taken from [8] and those at $V_f = 30$ and 35% were obtained in the present experiment. As seen, the tensile strength obeys the ROM strength predictions up to a fibre volume-fraction of approximately $V_f = 40\%$. For the high-temperature strength measurements,

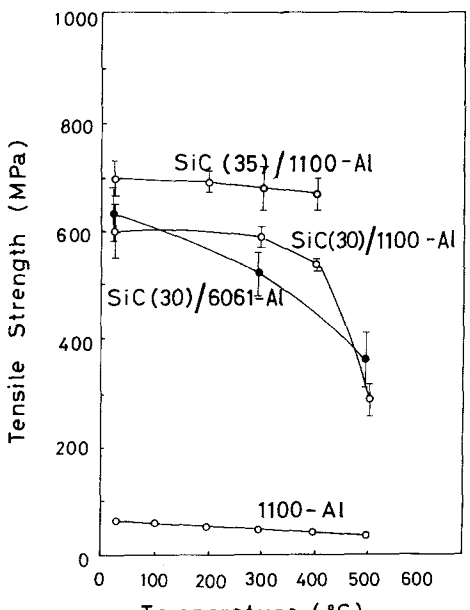


*Figure 4* Tensile strength of SiC fibre–Al as a function of test temperature. The numerals in parentheses indicate the fibre volume-fractions.

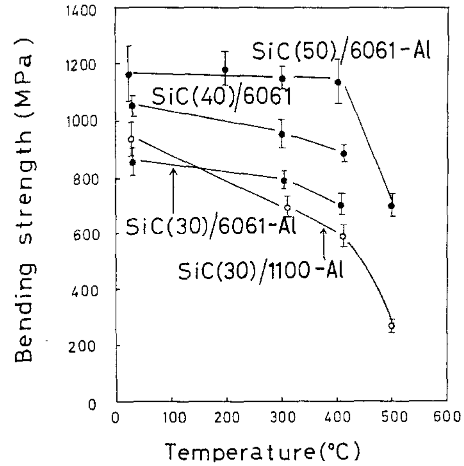


*Figure 5* Bending strength of SiC fibre–Al as a function of test temperature. The numerals in parentheses indicate the fibre volume-fractions.

therefore, SiC fibre–Al composites with $V_f = 30$, 35 and 40% were prepared. For reference purposes, SiC fibre–Al composites with $V_f = 50\%$, with a tensile strength which deviates from the ROM predictions were also prepared.

The high-temperature tensile and bending strengths of the SiC fibre/6061–Al and SiC fibre/1100–Al composites are shown in Figs 4 and 5, respectively. In the bending strength measurement at 500° C, because the specimen did not break, the maximum strength value is shown in Fig. 5. Fig. 4 also shows the tensile strength at high temperatures of a 1100–Al specimen without reinforcement fibres, prepared by a procedure similar to that shown in Fig. 1.

As seen in Figs 4 and 5, tensile and bending strengths of the respective Al composites remain nearly constant in the temperature range from a room temperature up to 400° C. However, at 500° C, the tensile strength for SiC(30)/6061–Al and SiC(30)/1100–Al decreases; the bending strength for SiC(30)/1100–Al also decreases. On the other hand, the strength of the SiC(50)/6061–Al specimen deviates largely from the ROM tensile strength, and the specimen exhibits the same high-temperature strength characteristic as in SiC(30)/6061–Al or SiC(30)/1100–Al.

From the above results, in the temperature range from a room temperature up to 400° C the strengths are almost constant regardless of the SiC fibre volume-fraction; however, at 500° C they decrease. There is little difference in the temperature behaviour of the strengths of matrix 1100–Al and 6061–Al.

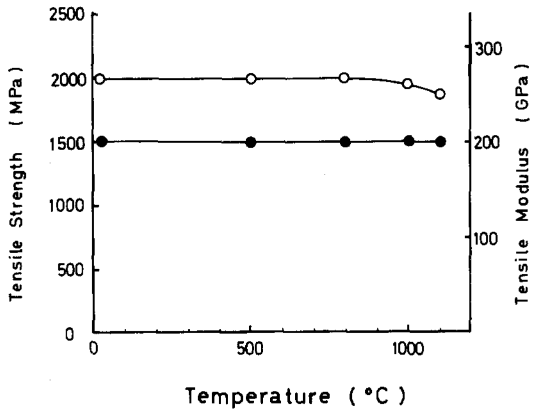


*Figure 6* Tensile strength of SiC fibre as a function of test temperature. ○: tensile strength; ●: tensile modulus.

The cause of the strength drop at 500° C in the SiC fibre–Al is considered as follows.

At first, the tensile strength deterioration of the reinforcement SiC fibre at high temperature was investigated. In vacuo, the SiC fibre keeps its strength at temperatures in the range from room temperature up to 1400° C. In the study by Yajima *et al.* [9], each fibre was held for 30 min at the testing temperature before the tensile strength measurement was taken at that temperature. In the present study the fibre tensile strength was measured at room temperature after keeping the fibre at each temperature for 1 h in air. As seen in Fig. 6, the strength remains constant up to 1000° C.

After each high-temperature tensile test, the tensile deterioration in the SiC fibres incorporated into the Al was examined. A SiC(30)/1100–Al composite, after tensile testing at 500° C was immersed in 30% NaOH solution for 24 h and then treated with hydrochloric acid for chemical separation of the aluminium matrix. The form of each SiC fibre thus extracted was found to be the same as that before incorporation into the aluminium. The tensile strengths of these SiC fibres was measured and was found to be about 2000 MPa (for a fibre diameter of 12.6 $\mu$m), which was the same as the tensile strength value of 2000 MPa (for a fibre diameter of 12.8 $\mu$m) measured prior to reinforcing. It may be concluded, therefore, that the SiC fibre was not deteriorated in strength by heating the SiC fibre–Al composite up to high temperature.

In tensile tests of the SiC(30)/1100–Al composite performed at room temperature and at 500° C, the shape of fracture and the fracture surface were observed by optical microscope and scanning electron microscope techniques, respectively. The results are shown in Figs 7 and 8, respectively. In Fig. 7a, at room temperature, fracture of both fibres and matrix occurs simultaneously; in Fig. 7b, at 500° C, the fracture appears more jagged, rather in the shape of a saw blade. In Fig. 8, in the surface fractured at 500° C (Fig. 8b) there is evidence of separation of the SiC fibres and the matrix and pull-out of the SiC fibres; these observations are not made for the surface fractured at room temperature (Fig. 8a). This difference in fracture behaviour is also indicated in Fig. 9, which shows the stress–strain curves for SiC(30)/1100–Al at room temperature, at 300 and at 500° C. At room temperature and 300° C, the beneficial effect of reinforcing with the SiC fibre is evident. At 500° C, however, the elongation due to increase in ductility of the matrix takes place, and the fracture occurs in steps. In bending tests also performed at 500° C, the wettability between SiC fibres and Al matrix deteriorates, leading to separation. This is observed in Fig. 10 which shows inter-lamina separation without breakage in a bending test of the SiC(30)/1100–Al composite at 500° C.

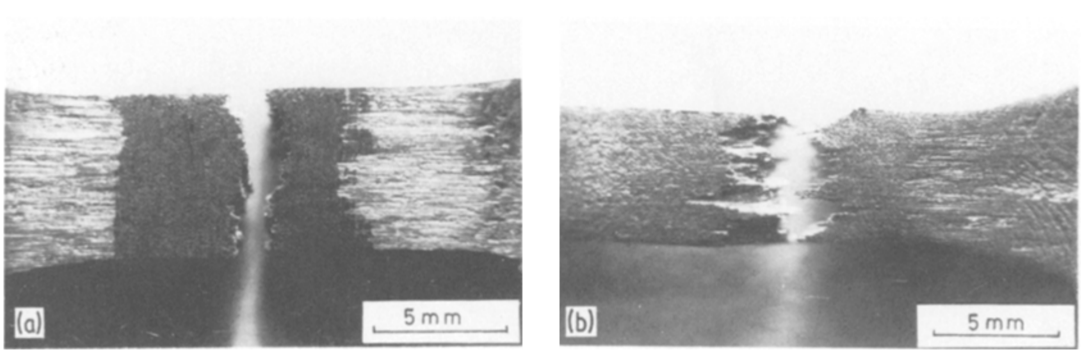


*Figure 7* Optical micrographs of tensile fracture specimens of SiC fibre–Al at (a) room temperature and (b) 500° C.

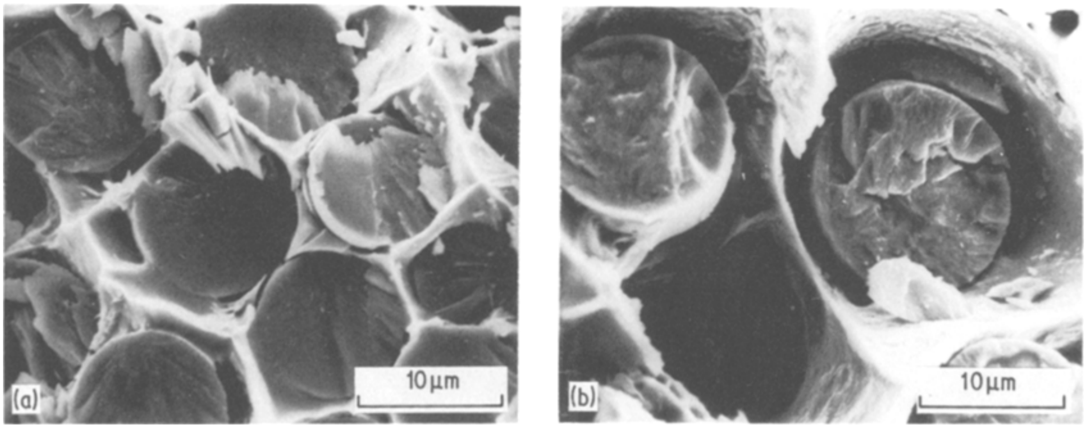


*Figure 8* Scanning electron micrographs of tensile fractured surfaces in SiC fibre–Al at (a) room temperature and (b) 500° C.

It is deduced that, at 500° C, the adhesion between SiC fibres and the Al matrix decreases, leading to considerable separation of the fibres and matrix. Consequently, there appears the pull-out of SiC fibres in the fracture surface. As a result of this loss of adhesion the transfer efficiency of stress in the composite drops off and the strength of the composite is reduced.

It is useful to compare the high-temperature strengths of the SiC fibre–Al composite with those of the aluminium composite reinforced with carbon fibre, graphite fibre or Fibre FP. However, since the respective measuring conditions differ, the comparison can only be qualitative.

Khan [10] examined the tensile strength of the graphite fibre ($V_f = 25$ to 30%) reinforced aluminium at high temperature. He measured the strength of each sample at room temperature after keeping each at its test temperature for 24 h in air: the strength (~560 MPa) was seen to be unchanged up to 500° C and then to decrease so that a drop of 20% was measured at 550° C. Pfeifer and Kinna [1] examined the tensile strengths of three kinds of graphite-fibre reinforced aluminium composites both at room and elevated temperatures: T50/201–Al ($V_f = 30\%$), HM3000-3/201–Al ($V_f = 34\%$) and GY70/201–Al ($V_f = 31\%$). Their tensile strengths at room temperature were found to be 569, 804 and 637 MPa, respectively. Their strengths were unchanged at temperatures up to 316° C, and at higher temperatures their strength decreased. At 370° C, the reductions in room-temperature tensile strengths of T50/201–Al, HM3000-3/201–Al and GY70/201–Al are 16, 22 and 11%, respectively. In T50/201–Al at 482° C the reduction is 30%. Champion, Krueger, Hartmann and Dhinga [2] measured the tensile and bending strengths of Al–2.0 to 2.4 wt % Li reinforced with aluminium oxide fibre (Fibre FP)

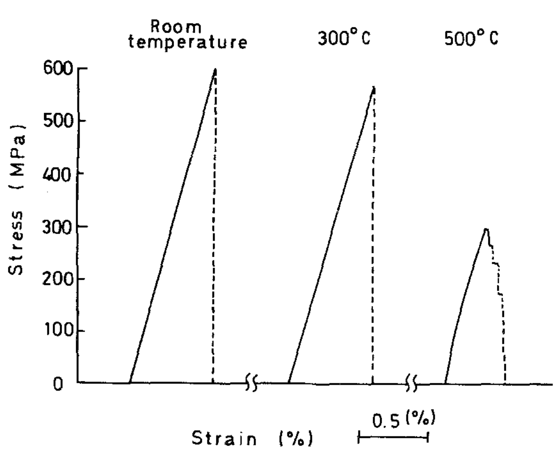


*Figure 9* Stress–strain curves of SiC fibre–Al at room-temperature, 300° C and 500° C.

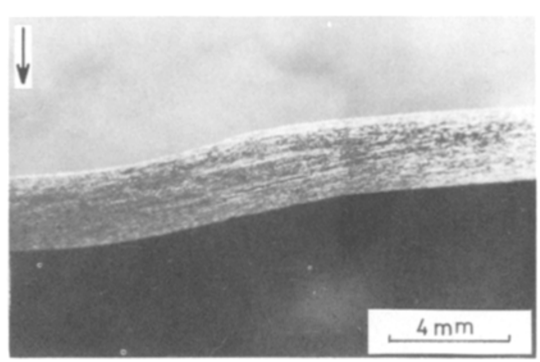


*Figure 10* SiC fibre–Al specimen shown after a bending test at 500° C showing inter-lamina separation. Stress was applied to the specimen in the direction of the arrow.

($V_f = 55\%$), developed by Du Pont, at temperatures in air (each sample was held at the test temperature for 30 min before each measurement was taken). The bending strength of about 1030 MPa at 20° C was seen to be unchanged up to 316° C; at higher temperatures the bending strength decreased gradually and at 482° C and 538° C the strength was seen to have dropped by about 20% and 30%, respectively.

Therefore, it appears that the relations between temperature and strengths observed for the above described composites is almost the same as that seen for the SiC fibre–Al composite.

## 4. Conclusion

The high-temperature strengths of the Al composites reinforced with $V_f = 30$, 35, 40 and 50% SiC fibre, and with SiC fibre derived from polycarbosilane, have been measured.

(a) The SiC fibre–Al composite retains its strength for the temperature range from room temperature up to 400° C; however, at temperatures above 500° C the strength is observed to drop off.

(b) The drop in strength at 500° C is caused by the reduction in the transfer efficiency of the stress accompanying the decrease in adhesion between fibres and matrix as evidenced in the fibre–matrix separation.

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