Advanced Performance Materials, 2, 311–320 (1995)

A Study of Continuous Filament Reinforced Aluminum Matrix Composites

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Abstract. Some principal results of the research work on metal matrix composites at Beijing Institute of Aeronautical Materials, concerning CVD-produced continuous B and SiC filaments reinforced aluminum and its alloys, are summarized. The processing, fiber degradation, interface, mechanical properties and fracture behavior of the composites are discussed.

Keywords: aluminum matrix composites, boron fiber reinforced composites, silicon carbide fiber reinforced composites

Abbreviations:

CVD	chemical vapor deposition
MMCs	metal matrix composites
ROM	rule of mixtures

1. Introduction

Metal matrix composites have great potential for use in areas where high specific properties are required, such as in the aircraft and aerospace industries. Numerous varieties of systems with different combinations of reinforcements and metal matrices have been developed in recent 30 years. Among them, aluminum matrix composites have still been receiving great attention in both research and applications. Beijing Institute of Aeronautical Materials has been doing research on boron fiber and aluminum matrix composites since 1972 and the main activities include:

- Chemical vapor deposition process for boron filament;
- Hot diffusion bonding process for B/Al and SiC/Al;
- Con-clad bending process for forming B/Al shapes;
- Hot isostatic pressing process for fabricating composite tubes;
- Special casting process for SiC/Al;
- SiC particle reinforced aluminum and its casting process;
- Interfacial phenomena and fracture behavior of B/Al and SiC/Al.

This paper has summarized some principal results of the study on boron and silicon carbide filaments reinforced aluminum.

2. Boron filament reinforced aluminum

The boron filament used in this study was manufactured by chemical vapor deposition process in our laboratory. The filament was 140 μm in diameter, with tungsten core and

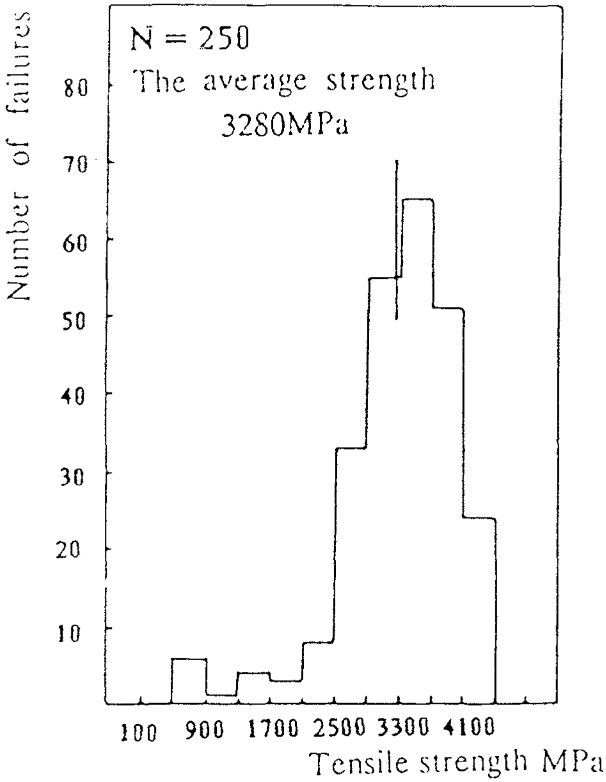

Figure 1. Typical histogram of tensile strengths of boron filaments.

3 μm thick B_4C coating which inhibits the interfacial reaction with aluminum matrix during the subsequent processing (hot pressing). The average tensile strength and modulus of the filament ranged from 3000 to 3500 MPa and from 360 to 400 GPa respectively, with a density of 2.5 g cm^{-3}. The typical histogram of the strengths is shown in Fig. 1.

The boron filament reinforced pure aluminum sheets were fabricated by hot diffusion bonding process in vacuum at 520–580°C under 50–70 MPa with dwell time of 20–90 min using a preform material of filament/foil with volatilized binder made by drum winding. The volatilized binder was removed by evacuation during the processing. The resulting composite sheets 1 mm thick were unidirectionally reinforced and contained 50 vol.% filament. They were examined by optical micrography, SEM, electron microprobe, X-ray diffraction and mechanical tests using straight sided tensile specimens of 10 × 75 mm with a 25 mm gauge length in the middle and tabs bonded on both ends.

2.1. *Interface*

It has been reported [1, 2] that bare boron filament without coating is prone to react with aluminum matrix during processing because of its activity, producing aluminum borides (AlB_2, AlB_{12}, etc.) on the interfaces, degrading the filaments and reducing the properties of the composites. To avoid the interfacial reaction, SiC or B_4C coatings are generally applied

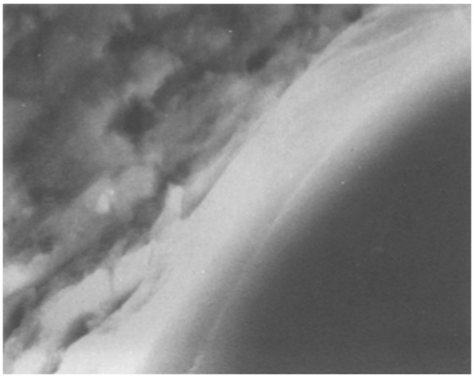

Figure 2. **Secondary electron imagine of the B/Al interface.**

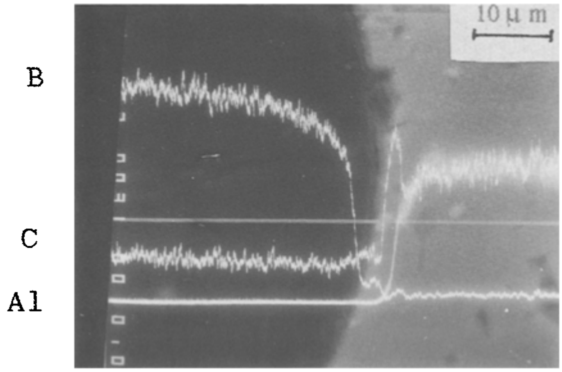

Figure 3. **Linear distribution of B, Al and C near the B/Al interface.**

on the surface of boron filament. In this study the boron filament was coated with B_4C which has better performance than SiC coating. Figure 2 shows a typical B-B_4C-Al interface of the hot diffusion bonded sheets. Electron microprobe analysis showing the linear distribution of elements B, Al, C in the interfacial area is given in Fig. 3. The microstructure and the element distribution were found quite normal near the interfacial area. X-ray diffraction analysis did not detect any borides on the interface, even after a long thermal exposure of the B/Al sheets at 550°C for 4–12 h, which is consistent with the microprobe analysis. Thus it can be concluded that the B_4C coating excellently protects the boron filament from the reaction with aluminum matrix.

2.2. *Processing conditions of hot diffusion bonding*

The predominant processing parameters of hot pressing are temperature, pressure and dwell time. Figure 4a demonstrates the results of bonding in the function of temperature and dwell time at a pressure of 50 MPa. The lower left area under the curve is corresponding to the poorly bonded composite sheets because of insufficient temperature and time, resulting

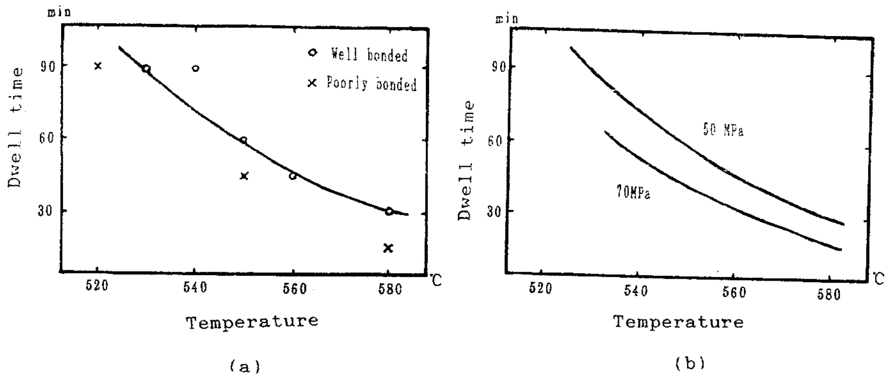

Figure 4. Influence of hot pressing parameters on diffusion bonding: (a) at 50 MPa, (b) at different pressures.

in low strengths, extensive fiber pull-out and delamination in tensile tests. The upper right area over the curve indicates the fully bonding conditions which produced dense and compact B/Al sheets without delamination and debonding. Increasing pressure can reduce the required temperature or dwell time for good bonding. As seen in Fig. 4b, when the pressure increased from 50 to 70 MPa, the area of full bonding extended and the curve moved down.

2.3. *Fracture behavior*

As mentioned above, the results of diffusion bonding are dependent on the conditions of hot pressing. Insufficient temperature, pressure and dwell time during hot pressing result in poor bonding and weak interfacial shear strengths between the filament and the matrix. The tensile specimens from these sheets fractured with delamination and extensive fiber pull-out, and a brush-like form appeared, causing very low strengths. However, excessively high temperature and pressure of the process lead to extremely strong bonding between the filament and the matrix and high interfacial shear strengths, resulting in the specimens fracturing at medium strengths and a relatively flat fracture surface with little fiber pull-out. Only the sheets diffusion bonded under appropriate parameters of hot pressing exhibit high tensile strengths with an uneven fracture surface and some fiber pull-out. These results are clearly illustrated in Fig. 5 and the fracture surfaces can be defined as three types: brush-like, pull-out formed and flat.

It is believed that extremely strong bonding between fiber and matrix is unfavorable to the mechanical properties. The reason is that when a transversely propagating crack reaches the interface, the filament and the matrix will not debond, forming a high stress concentration at the tip of the crack on the filament surface and causing a low stress fracture of the filament. The crack is very "easy" to propagate through all interfaces and filaments, which results in relatively low strengths and flat fracture surface of the composites. In the case of appropriate parameters of hot pressing, medium bonding strengths of the interface are formed in the well diffusion bonded composite sheets. The filament and the matrix will debond as a crack reaches the interface, causing crack deflection and blunting, which retards or stops the crack propagation. The fracture surface exhibits an uneven form with some fiber pull-out, resulting in high tensile strengths. Figure 6 is the SEM fractographs of these two cases, clearly showing the difference of the fracture behavior.

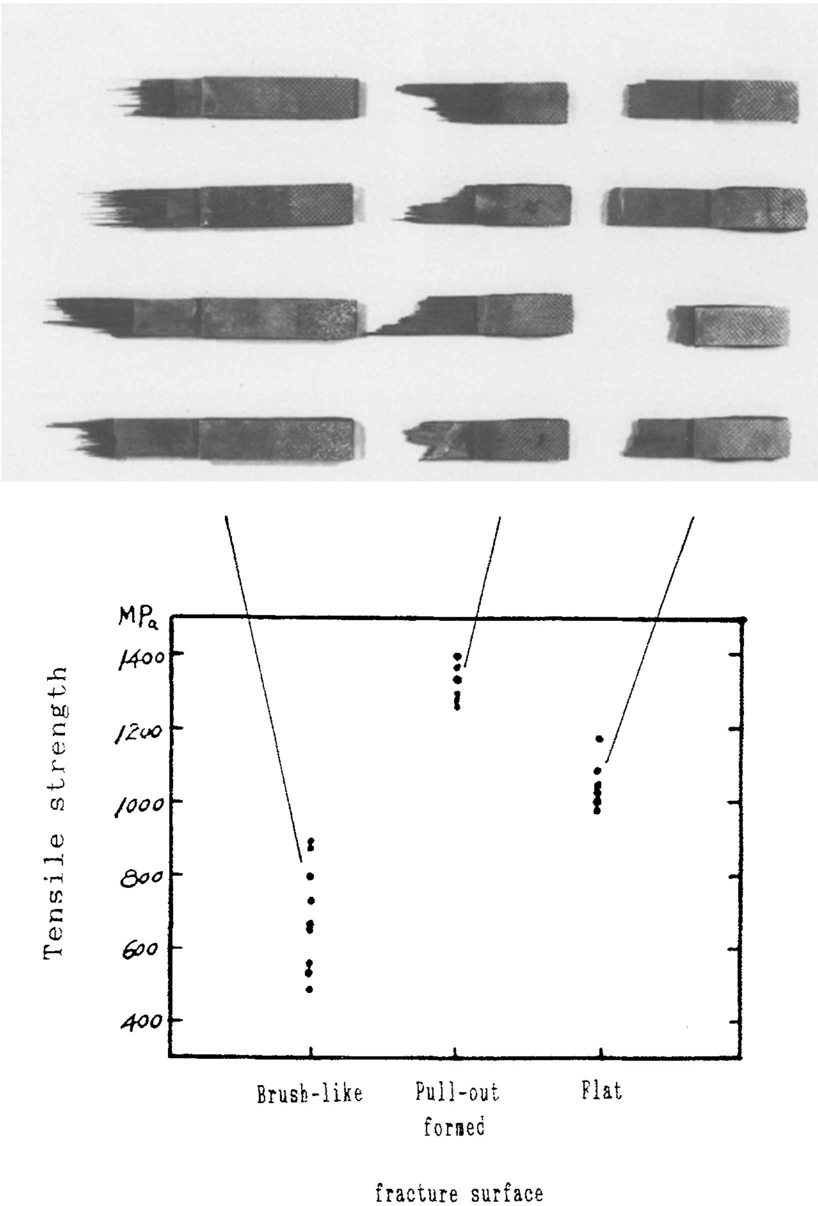

Figure 5. Relationship between tensile strengths and morphology of fracture surfaces.

3. CVD SiC filament reinforced aluminum

A vacuum suction casting process was devised for manufacturing composites of aluminum reinforced with CVD SiC filaments. The filaments were inserted into a steel tube with one

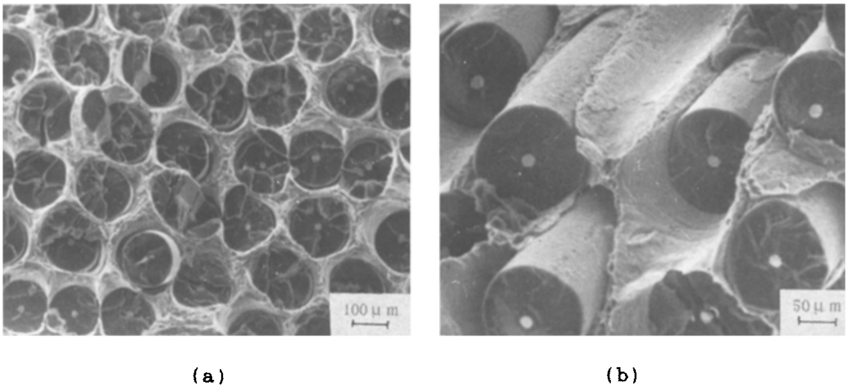

Figure 6. SEM fractographs of B/Al tensile specimens: (a) flat fracture surface, (b) pull-out formed fracture surface.

end sealed by an aluminum stopper and the other end connected to a vacuum system. The tube containing the filaments was preheated in a small tubular furnace to an appropriate temperature during continuous evacuation (3–5 Pa), and then the end with the stopper was immersed in molten aluminum in a large furnace. The stopper melted at once and the molten aluminum was sucked into the tube, infiltrating the filaments. After cooling, the steel tube was etched away in 50% nitric acid, leaving the SiC/Al rod intact.

Three types of CVD SiC filaments were used in the experiment: SCS-2 and SCS-6 coated filaments with carbon core, both 140 μm in diameter from TEXTRON (USA), and uncoated filament with tungsten core, 100 μm in diameter from SIGMA (FRG). Cast aluminum alloy Al-10% Si was chosen as a matrix because of its high fluidity, low melting point and less probability of Al_4C_3 formation by reaction with SiC in the melt according to the Al-Si-C ternary phase diagram [3]. The results of infiltration were examined by micrographs of the cross sections of composite rods with 50 vol.% filament to assess wettability and bonding between the filaments and the matrix. To investigate possible degradation of the filaments, they were extracted by etching away the aluminum matrix with NaOH solution. The extracted filaments and the composite rods (4 mm in diameter) were tensile-tested using specimens 120 mm long with a gauge length of 25 mm. Other properties were also examined.

3.1. Wettability of SiC filaments in vacuum suction casting

Wettability of fibers is a prerequisite condition that must be satisfied in liquid infiltration. The results of liquid infiltration with various combinations of the two main processing parameters, namely, the filament preheating temperature and the temperature of molten aluminum, which determine the conditions and results of wettability, infiltration, solidification and bonding, are summarized in Fig. 7. Low temperature is always recommended as there is less degradation of the fiber, if wettability and full infiltration can be achieved. It has been found that full infiltration was obtained at a melt temperature as low as 700°C with filament preheating to 750°C, which is much lower than the wetting temperatures published in literature [3, 4]. This is due to the good wettability achieved under the favorable

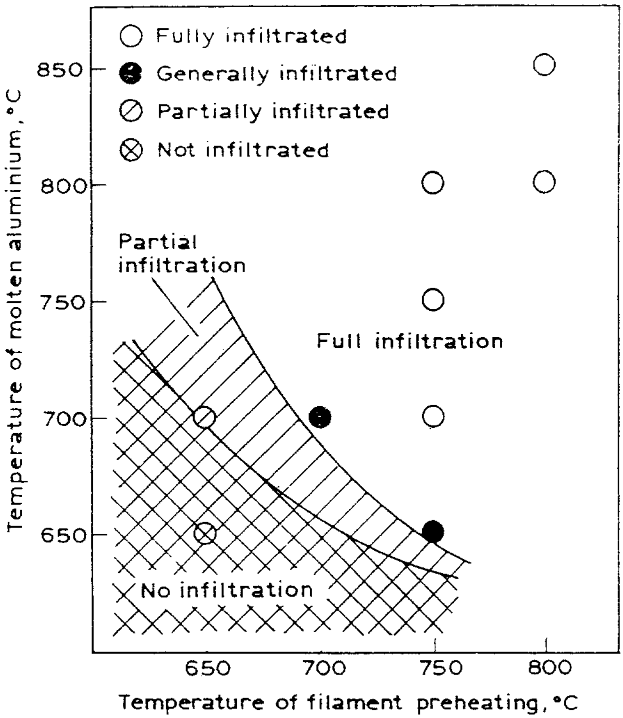

Figure 7. The effect of liquid infiltration at various temperatures.

conditions specific to this casting process, namely, (1) no air between the filaments and adsorbed on the filament surfaces, which activated the filament surfaces, speeded up the aluminum flow and promoted the process of infiltration, (2) freedom from the interference of aluminum oxide films due to melting the stopper in the depths of the molten aluminum and sucking only the "clean" aluminum into the steel tube, and (3) the presence of atmospheric pressure.

A cross section of a 6 mm composite rod with 50 vol.% SCS-6 filament is shown in Fig. 8. The filament distribution on the whole can be considered satisfactory, but it is dense in some areas and sparse in others and usually has a roll structure. This is due to processing the filaments by hand and can be eliminated by using woven fiber preforms. The micrograph in Fig. 9 demonstrates that the filaments are well infiltrated.

3.2. *Filament degradation in vacuum suction process*

Fiber degradation is a severe problem in the manufacture of MMCs. The low wetting temperatures and short processing time in this process provided a favorable basis to minimize the reaction between filaments and matrix and therefore the filament degradation. Figure 10 shows the tensile test results of the extracted filaments after casting at various temperatures of molten aluminum with the same filament preheating temperature of 750°C. The SCS filaments exhibited an excellent stability against the molten aluminum and retained almost their initial strengths after casting, whereas the uncoated SIGMA filament showed

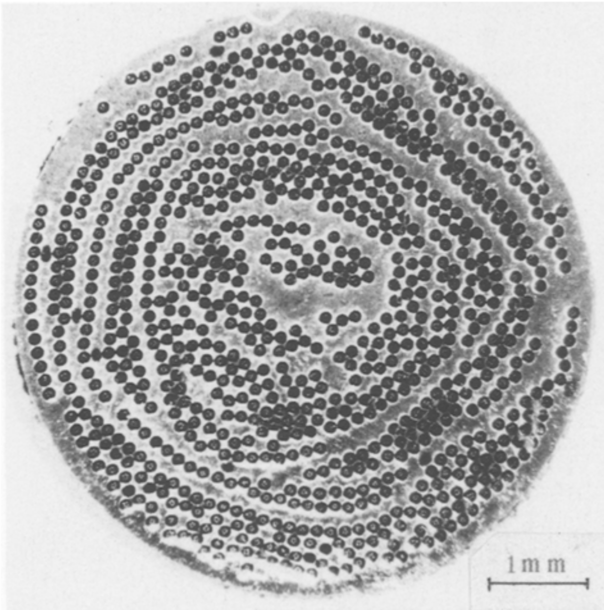

Figure 8. Cross-section of a fully infiltrated SiC/Al rod, 6 mm in diameter with 50 vol.% SCS-6 filament (filament preheating 750°C, molten aluminum 750°C).

severe degradation, losing about half its initial strength and retaining a tensile strength of only approximately 1500 MPa. Thus it can be concluded that the uncoated SiC filament is unsuitable for incorporation in an aluminum matrix by means of liquid infiltration processing.

3.3. Mechanical properties of SiC filament reinforced aluminum

Figure 11 shows the tensile strength and modulus of 4-mm composite rods cast at various melt temperatures with the same filament preheating temperature of 750°C. In the melt temperature range 700–800°C the composite strengths decreased, as expected, with increasing temperature. The highest strength of 1700 MPa was obtained in the composite reinforced with 50 vol.% SCS-6 filament for the melt temperature 700°C and the strength then decreased slightly to 1600 MPa at 800°C. SCS-2 reinforced aluminum exhibited somewhat lower strengths (1560–1190 MPa), although the strengths of the extracted and as-received SCS-2 and SCS-6 filaments were similar. It can be concluded that the SCS-6 filament is better than SCS-2 for incorporation in an aluminum matrix by infiltration, which is probably associated with the multiple-layer structure of the thicker SCS-6 coating. The 50 vol.% uncoated SIGMA filament reinforced aluminum had very low strength (less than 400 MPa), which was much lower than even the 50% strength of the degraded filament (the ROM prediction). This presumably indicated a detrimental structure of the interface. The tensile moduli were similar for all of the composite rods and ranged from 200 to 237 GPa, no matter whether the filaments degraded or not.

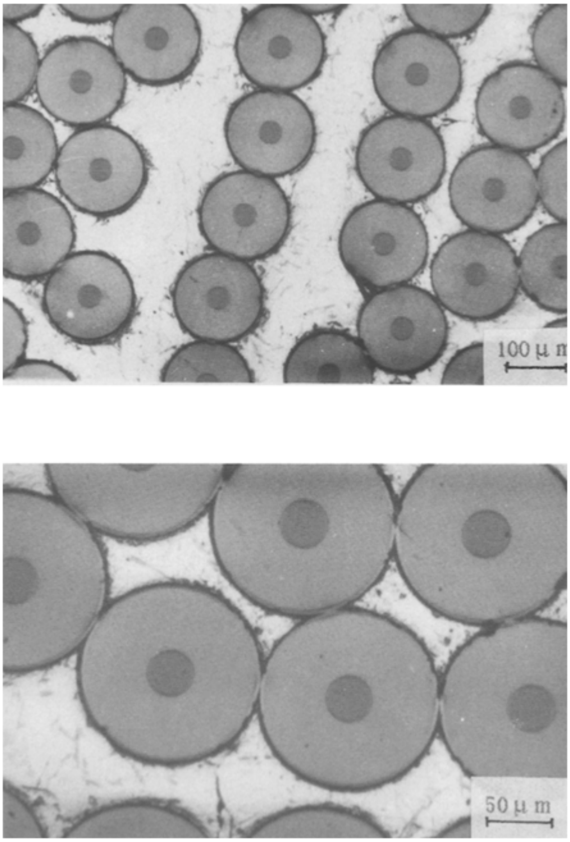

Figure 9. Micrographs of fully infiltrated SiC/Al rod with 50 vol.% SCS-6 filament (filament diameter 140 μm).

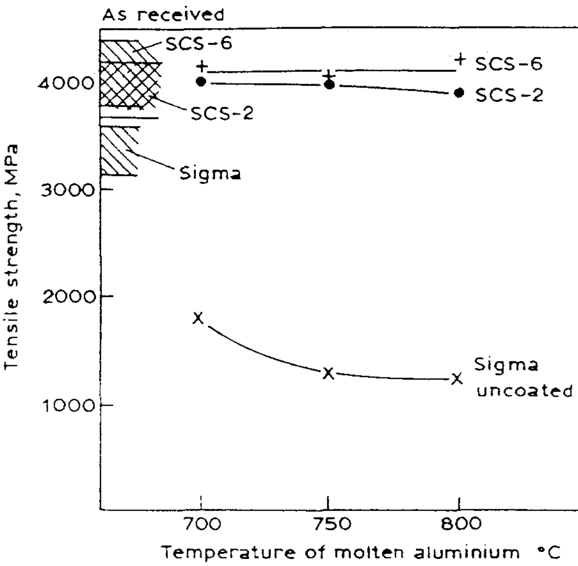

Figure 10. Strength degradation of SiC filaments extracted from matrix after casting vs temperatures of molten aluminum (filament preheating 750°C).

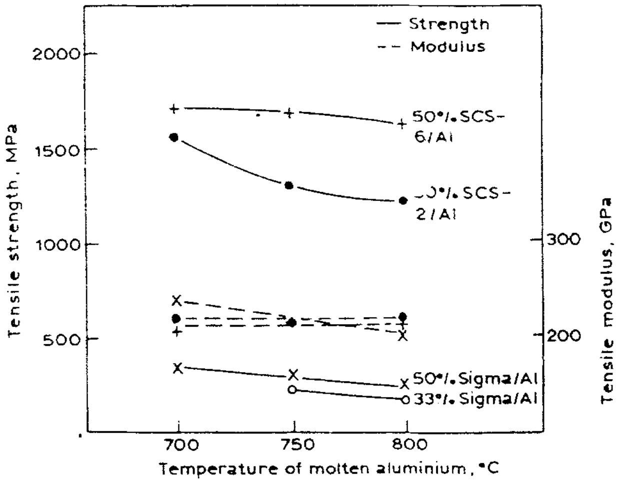

Figure 11. Mechanical properties of CVD SiC/Al cast at various temperatures of molten aluminum (filament preheating 750°C).

Other properties have also been tested. The typical properties of a 50 vol.% SCS-6 filament reinforced Al-10% Si alloy manufactured by the process are as follows:

Tensile strength	1600–1700 MPa
Tensile modulus	208–220 GPa
Compression strength	1740–1810 MPa
Compression modulus	212–215 GPa
Shear strength (transverse)	240–270 MPa
Coefficient of thermal expansion	3.6×10^{-6}°C^{-1}(20–300°C)

The tensile strength obtained is higher than most published data in the literature for CVD SiC filament reinforced aluminum.

Using this process, unidirectionally reinforced tubes of 20-mm outside diameter with wall thicknesses of 2 and 3 mm were successfully cast.

Acknowledgments

The authors would like to thank Advanced Materials Committee of China for the financial support to this study.

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