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Products of interaction in the Al–Si alloy–carbon fibre system

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Samples of a composite material were obtained by pressure infiltration with AL2 melt of a carbon tape. Products of interaction forming on the fibre–matrix interfacial boundary were investigated. It has been found that Al_4C_3 and SiC phases and silicon crystals are formed. An increase of the contact time between a fibre and the melt, and melt temperature and the infiltration pressure leads an increase in the Al_4C_3 carbide phase quantity and to the bond strength on the fibre–matrix interfacial boundary. Here with tensile strength tests, the character of fractures changes from tensile (with noticeable fibre pull-out from the matrix) – to ductile; shear strength is increased.

1. Introduction

Formation of the carbide phase in the composite material (CM) aluminium alloys–carbon and its effect on the mechanical properties of CM are studied in detail relating to isothermal annealing [1–3]. It has been shown that the growth of aluminium carbides on the interfacial boundary results in a lowering of CM strength.

There are no data on carbide formation in CM production, on the effect of the production method on composition, morphology and quantity of the carbide phases. Meanwhile, the instability of carbon–aluminium CM properties is probably connected with uncontrolled formation of carbides during CM production.

One possible way to limit carbide formation is to alloy aluminium alloys with elements very similar to carbon and changing the interaction character on the interfacial boundary. Silicon is one such element. Portnoj *et al.* [4, 5] noted that carbon solubility is lowered in aluminium melts containing 7 to 10% Si. It is supposed that the reaction of Al–Si alloys with carbon fibres occurs slower and thus the Al_4C_3 phase content in CM is reduced.

However, there are no experimental data on the peculiarities of the interaction in the carbon fibre–Al–Si alloy system. In this connection the aim of the present investigation was to determine the composition and morphology of the interaction products on the interfacial boundaries AL2 alloy (about 12 wt % Si)–carbon fibres in CM production by the liquid-phase method and to analyse the character of the bond between a fibre and the matrix.

2. Materials and methods of investigation

Investigations were carried out on CM samples obtained by vacuum-compression infiltration of a carbon tape by AL2 alloy. The fibres content of the CM samples was 55%.

The composition quality was evaluated according to fracture character, results of tensile tests and interlayer shear under three-point bending. Flat samples of 2mm × 10 mm × 45 mm were used in investigations, providing variation of L_s base. Shear stength was determined from the relation $L_s/d < 5$, where $d = 2$ mm is the diameter of the bending punch, and tensile strength for $L_s/d \geqslant 15$ [6].

Using electron microscopy, products of the interaction between a fibre and the matrix were revealed, while investigation of the lateral surface of fibres etched from the matrix and also extracted carbon replicas from fractures of CM samples was undertaken. To the preserve Al_4C_3 carbide on the fibres the matrix was dissolved in

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a non-aqueous organic solvent. Electronograms were made from the particles extrated from carbon replicas. The content of the carbide phase in the CM was determined by quantitative chemical analysis. Calculation of the phase quantity was made according to the weight unit of a carbon tape in CM. The intensity of element distribution was registered using a "Camebax" micro-analysator.

3. Results and discussion

Compressive infiltration of a carbon tape provides satisfactory occupation of interfibre spaces by the matrix: it is found between the plaites as well as in capillaries inside the plaites.

Carbon relicas reveal fine fraction celavage of the carbon fibres, and spots of ductile or quasi-ductile matrix fracture (Fig. 1). The interaction products are found on the interfacial boundaries as isolated particles with arbitrary orientation with relation to the fibre. The particles adhere to the matrix side. The extracted particles are identified by electronography to be Al_4C_3.

Particles of the aluminium carbide are found on the fibres etched out of the matrix as flat six-angle plates with chaotic distribution on the surface (Fig. 2). On the fibres of one plait and sometimes in the range of one elementary fibre parallel to colonies of densely distributed Al_4C_3 plates, places are found with separate crystals and also places free from carbide crystals. Such an irregularity of carbides formation is probably connected with the nonhomogeneous structure of the carbon fibre surface. At first the carbide particles grow into the matrix and in later stages of the reaction their inclusion into the fibre occurs (Fig. 2b). This is also exhibited by pits on the lateral side of the fibre after the carbide fracture.

Increase of the infiltration temperature and contact time between the fibre and the melt leads to the growth of carbides which are already being formed and to the initiation of new ones, and to formation of the continuous carbide layer (Fig. 2c).

The formation of the aluminium carbide continuous layer may be prevented by silicon segregaton on the fibre–matrix interfacial boundary. Registration of silicon distribution intensity testifies that silicon concentrates around the fibres. As a result, formation of islands or a layer of silicon carbide on the fibre surface may occur (Fig. 3). SiC formation is confirmed by electronograms from the fracture of carbon tape–AL2 alloy samples.

The interface interaction may also be affected by growth of the initial silicon crystals from the fibre surface deep into the matrix by AL2 alloy crystallization. It is known that in alloys of pre-eutectic and eutectic composition polyhedral crystals of the initial silicon are often observed [7]. Their growth may be stimulated by change in the melt composition near the fibre surface due to silicon segregation. Fig. 4 presents the initial and eutectic crystals on the carbon fibres after aluminium and Al_4C_3 phase solution. Perfect facing of the initial crystals appears as a result of layer-by-layer growth out of the melt.

Quantitative chemical analysis of the aluminium carbide content has shown that the samples on ther AL2 alloy base contain less Al_4C_3 phase in comparison with the samples with a matrix from the pure aluminium obtained using the same conditions (e.g. 33 mg Al_4C_3 to

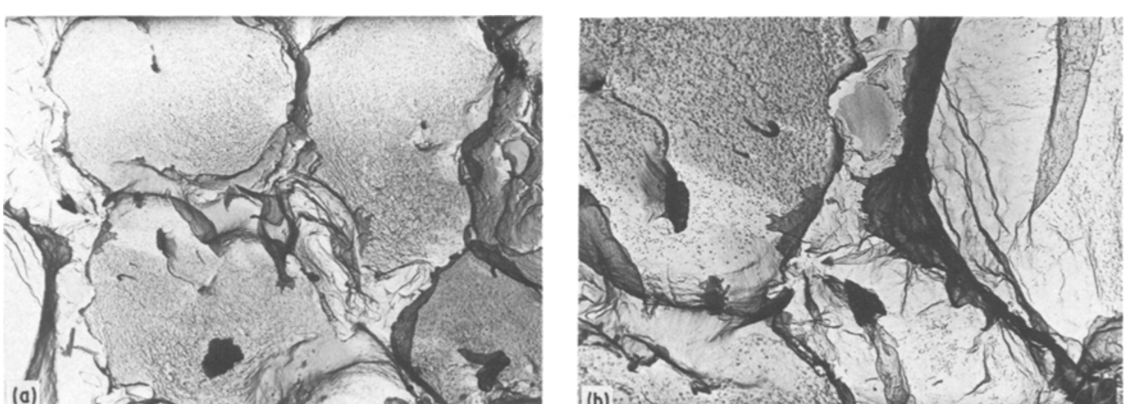

Figure 1 Replica from the transverse fracture of the composite material. (a) $\times 4500$; (b) $\times 11\,700$.

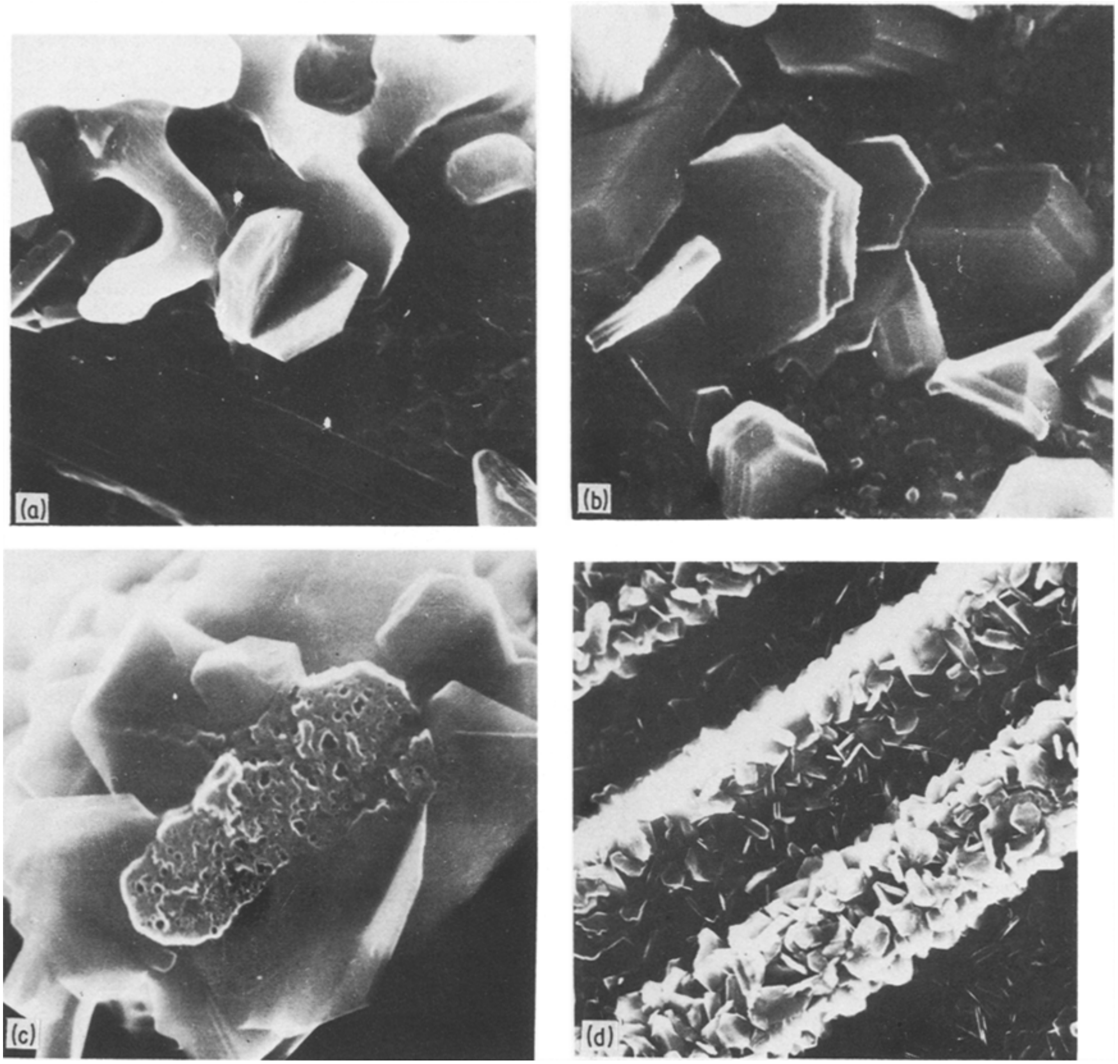

Figure 2 Surface of the carbon fibres with aluminium carbides: (a), (b) × 12 600; (c) × 16 800; (d) × 2520.

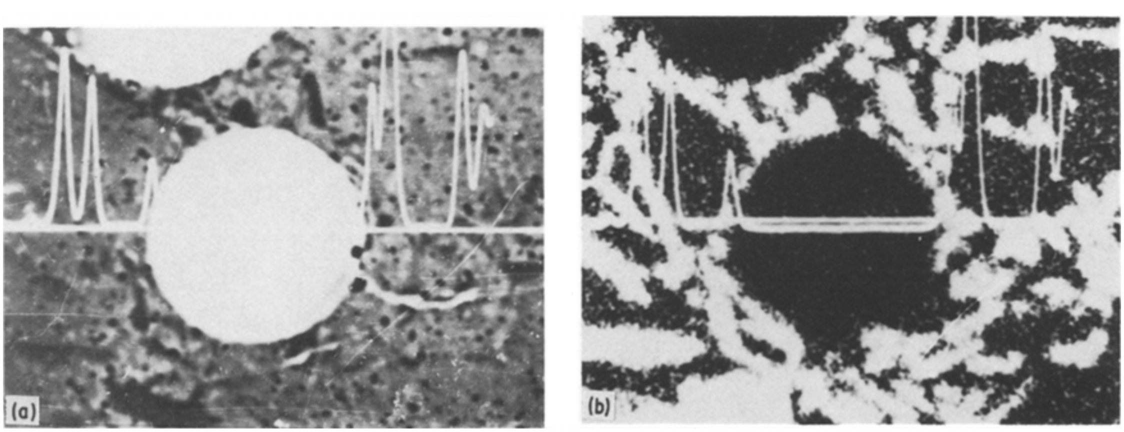

Figure 3 Silicon distribution in the CM sample–AL2 alloy–carbon fibre (a) and the sample photo in the characteristic silicon radiation against intensity curve (b). × 540.

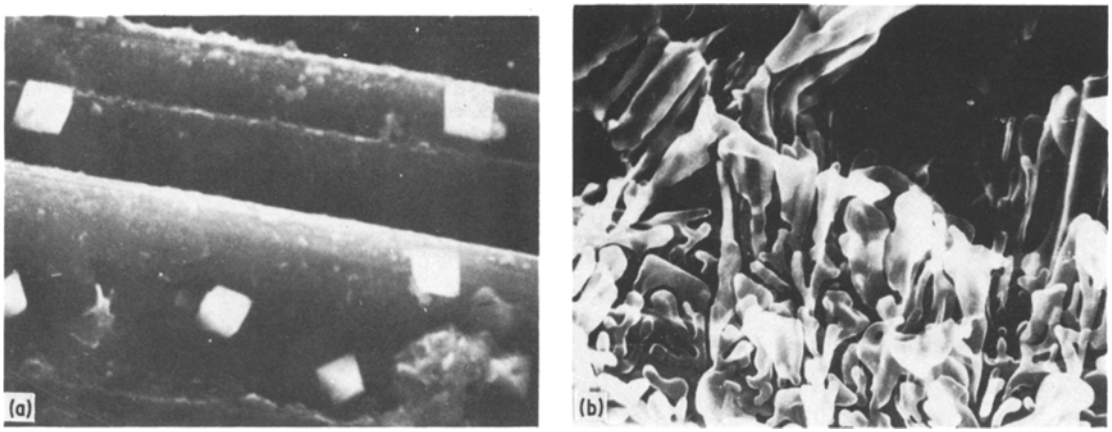

Figure 4 (a) The initial silicon crystals and (b) the silicon eutectic crystals on the surface of the carbon fibres etched from the matrix, (a) × 1350, (b) × 4500.

1 g carbon fibre compared with 58 mg Al_4C_3 1 g carbon fibre providing the maximum infiltration temperature).

Stresses are transferred from the fibre to the matrix through the carbide phase. The fractographic analysis has shown that fracture of such "cohesion bridges" occurs along the carbide–fibre boundary. The aluminium carbides are not found on the lateral side of the fibres pulled out of the matrix. It may be considered that due to physicochemical interaction in the carbon–aluminium composition the superposition of two types of bond between the fibre and the matrix (mechanical and reaction) takes place [8].

Quantitative chemical analysis has shown that an increase in infiltration pressure leads to a rising concentration of carbide phase in the samples. It is probably connected with an increase in the contact surface between the melt and the fibre. Under high-temperature infiltration, the dependence of the Al_4C_3 phase quantity on pressure is more prominent. Increasing infiltration temperature, and time of interaction of the fibre with the melt also leads to an increase in the quantity of carbide phase in the composition (Fig. 5). As a result, the bond on the interfacial boundary improves.

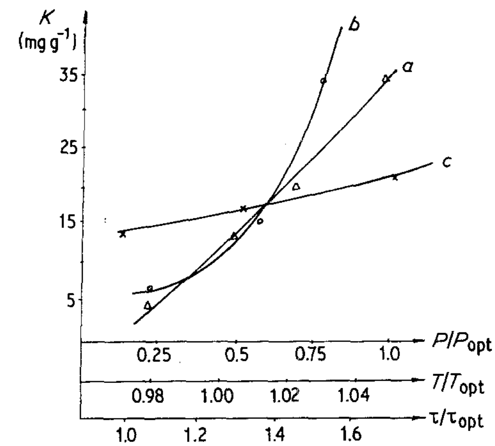

Figure 5 Dependence of Al_4C_3 quantity in CM on (a) pressure, (b) temperature, and (c) infiltration time.

Depending upon the bond strength on the fibre–matrix interfacial boundary, a change of fracture from tensile (with noticeable pull-out of the fibres from the matrix) to ductile is observed.

Mechanical properties of the AL2 alloy–carbon fibre composition were studied under various infiltration conditions. Increasing Al_4C_3 phase content leads to an increase in shear strength. The tensile strength is described by the curve with a maximum ($\sigma_g = 910$ MPa) corresponding to $l/d \approx 100$, where l is the length of fibres pulled out of the matrix; d is the fibre diameter (Fig. 6). Chemical analysis has shown that the Al_4C_3 phase quantity in such CM reaches 13.8 mg to 1 g of carbon fibre. Here the average size of the carbide phase crystals is equal to about 1 μm.

4. Conclusion

The interaction products have been investigated on the interfacial boundary in the carbon tape–AL2 alloy composition with respect to vacuum-compression infiltration conditions. Formation of the Al_4C_3, SiC phase and silicon crystals were found. The samples where fracture

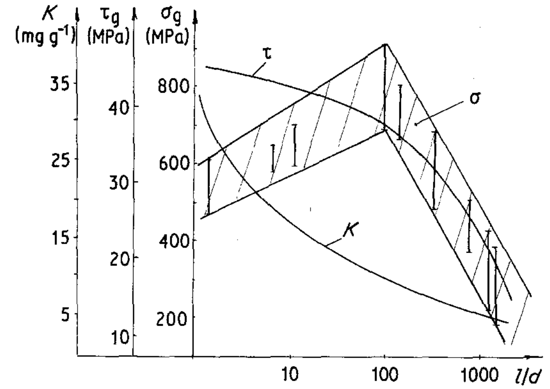

Figure 6 Tensile and shear CM strength in the bend test and Al_4C_3 phase content, depending on infiltration conditions.

had the relationship of length of fibre pulled out of the matrix to diameter $l/d \approx 100$ exhibit the best mechanical properties. The quantity of aluminium carbide in such a composition is equal to 13.8 mg Al_4C_3 per 1 g carbon fibre.

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