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Interface characteristics and mechanical properties of carbon fibre reinforced copper composites

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Interface characteristics of carbon fibre reinforced copper matrix composites materials with various interface states and their effect on the flexural strength of composites have been studied. Interfacial states are mechanical bonding, dissolution bonding and reaction bonding. To a certain extent, raising the interfacial strength enables an increase in the flexural strength due to prevention of carbon fibre being pulled out under low stress during fracture process of composites. Raising the interfacial bondage strength, causes the brittleness of composites to increase; the fracture surface of composites is converted from a fibre pull-out model to a fibre even model. While strengthening the interface bondage, the extent of chemical reaction and dissolution at the interface must be controlled to avoid degrading the carbon fibre.

1. Introduction

Carbon fibre reinforced copper matrix composite materials (hereinafter referred to as C/Cu composites) with a low thermal expansion coefficient, a high electric conductivity and a high thermal conductivity may be applied as a contact material, brush and substrate for a silicon semiconductor element [1].

Because of the poor wettability between carbon fibre and copper [2], a random carbon fibre/copper composite with isotropic characteristic of thermal expansion coefficient, when subjected to a temperature higher than the softening of the copper matrix, gives an abnormal volume change resulting in deformation and breakdown of the composite for more than 20 vol % of the carbon fibre [3]. So it is important to increase the interfacial strength of composites to resist any debonding of the interface.

Interfacial characteristics of metal matrix composites are the most important factors influencing many of the mechanical properties of composites. Adequate interaction between matrix and carbon fibre on which interfacial strength depends is essential for the C/Cu system in order to enable a maximum loading of the carbon fibre.

A considerable amount of research effort has been invested in studying interfacial compatibility between carbon fibres with metals. An interaction between carbon fibres and iron or nickel will increase the interfacial strength, but carbon fibres will be degraded through intensive chemical reaction or recrystallization with a consequent loss of strength [4, 5].

The systems for study in this investigation consist of carbon fibre, Cu–Ni coated carbon fibre and Cu–Fe coated carbon fibre reinforced copper composites, hereinafter referred to as C/Cu, C/Cu–Ni and C/Cu–Fe composites, respectively. The Cu–Ni and Cu–Fe duplex coatings were coated on the carbon fibre surface by continuous electroplating, respectively. Flexural strengths of the composites were measured and interface structures of the composites were observed and analysed by transmission electron microscopy (TEM). The influence of interface status on the mechanical properties of composites is discussed.

2. Experimental procedure

The fabrication of composites is schematically illustrated in Fig. 1. Composites fabricated in this experiment consist of continuous fibre reinforced composites and short fibre (3 mm in length) reinforced composites. Conditions for the hot-press were: temperature 800 °C, pressure 36 MPa for 20 min. The hot-press was carried out in an argon atmosphere.

Flexural tests of composites were carried out in a model Mi44 testing machine with loading parallel to the hot-press direction. Results are the mean values of three separate measured data. Fracture surfaces of composites were observed by SEM. The interface zone morphologies of composites were observed with TEM and the interface structures were analysed by μ-μ diffraction.

3. Results and discussion

Flexural strengths, characteristic of fracture surface and interface bonding model are shown in Table I. Characteristics of the fracture surface and length of the fibre pullout depend on the interfacial strength. The length of fibre pullout is inversely related to interfacial strength [6]. From the length of fibre pullout on the composite fracture surface shown in Fig. 2b, Fig. 3b and Fig. 4b, interfacial strengths

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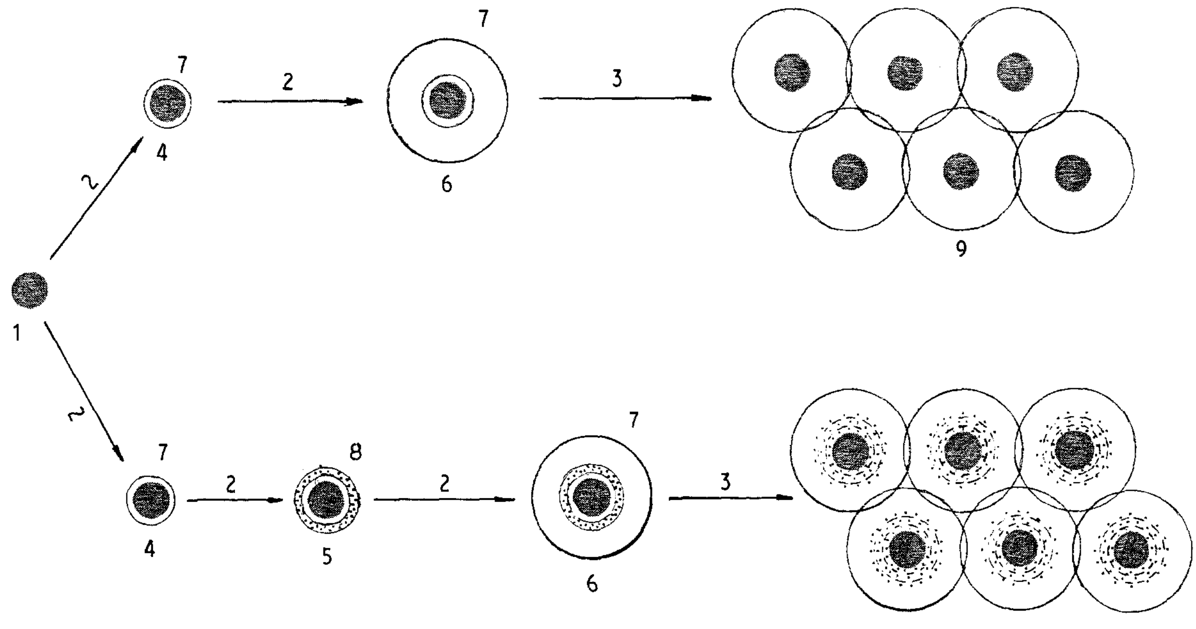

Figure 1 Schematic illustration of carbon fibre reinforced composite fabrication: 1. carbon fibre; 2. electroplating; 3. hot-press; 4. carbon fibre coated with Cu; 5. carbon fibre coated with Cu–Fe or Cu–Ni duplex coating; 6. precursor filament; 7. Cu; 8. Fe or Ni; 9. C/Cu composite; and 10. C/Cu–Fe or C/Cu–Ni composite.

TABLE I Characteristics and mechanical properties of composites

Kind of composite	Continuous fibre composites			Short fibre composites		Model of interfacial bonding
	V_f	σ (MPa)	Model of fracture surface	V_f (%)	σ (MPa)	
C/Cu	55 32	490 410	Long fibre pullout	34	250	Mechanical bonding
C/Cu–Fe	51	637	No fibre pullout	47	349	Chemical reaction bonding
C/Cu–Ni	36	458	Short fibre pullout	33	315	Dissolution bonding

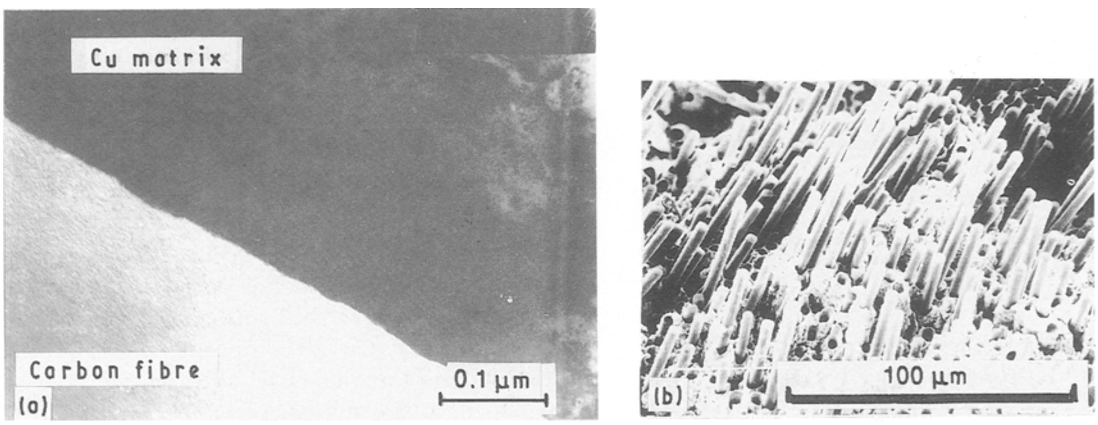

Figure 2 (a) TEM micrograph of interface and (b) SEM photograph of fracture surface of the C/Cu composite.

increase in the order C/Cu, C/Cu–Ni and C/Cu–Fe. Flexural strengths of C/Cu–Fe and C/Cu–Ni composites are larger than the strength of C/Cu composites at approximate fibre volume fractions (V_f).

3.1. Interface and fracture surface of C/Cu composites

There is no interaction at the copper/carbon fibre interface for C/Cu composites. The boundary of the carbon fibre and copper matrix is distinct and the copper matrix is detached from the carbon fibre in some places (Fig. 2a). This kind of interface is not strong enough to transfer the stress of the matrix to the carbon fibre. During the composite fracture process this interface is easily decohered and carbon fibres are pulled out under low stress. Flexural strength of C/Cu composites is relatively low and length of pull-out fibres is very long (Fig. 2b).

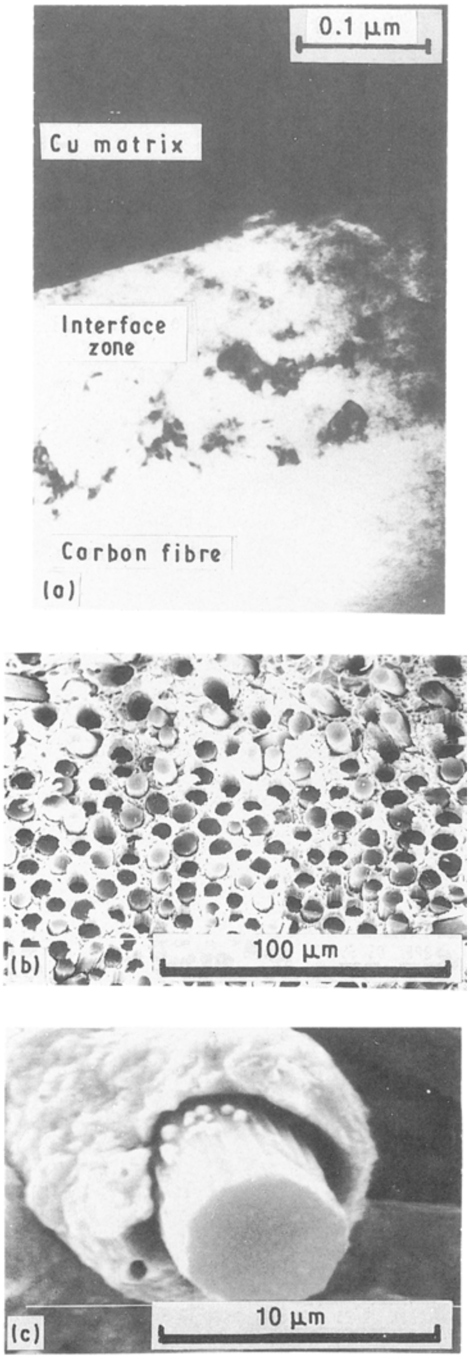

Figure 3 (a) TEM micrograph of interface and (b) and (c) fracture surface of the C/Cu–Fe composite.

3.2. Interface structure and fracture surface of C/Cu–Fe composites

An external layer of iron is able to diffuse through an internal copper coating given to the carbon fibre surface which reacts with the carbon fibre during the composites fabrication process as follows:

$$3Fe + C \rightarrow Fe_3C$$

The extent of this chemical reaction depends on the standard free energy of formation for Fe_3C and the concentration of iron on the surface of the carbon fibre [7].

Fig. 3a shows the morphology of C/Cu–Fe composite interface with an evident boundary between carbon fibre and interface zone. There is third phase (black grains in Fig. 3a) whose thickness is about 0.1 µm in the interface zone. After analysis by µ-µ diffraction, the new phase is polycrystalline Fe_3C [8] (corresponding to the discrete layer of particles on the surface of carbon fibre in Fig. 3c) which is a brittle phase and gives rise to the brittleness of the interface. The interface of C/Cu–Fe composites is strengthened by the pinning force of Fe_3C particles and it is too strong to decohere during a fracture process of the composite. Carbon fibre pullouts are not observed on the fracture surface (Fig. 3b). The composites are brittle fracture-type due to the brittleness of interface.

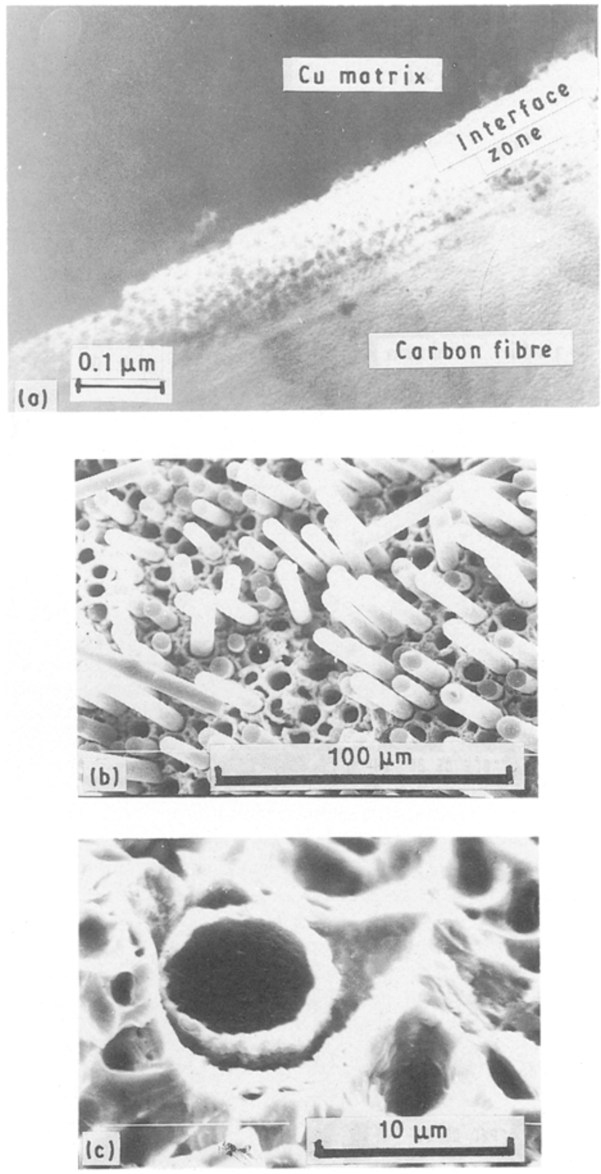

Figure 4 (a) Morphology of interface and (b) and (c) fracture surface of the C/Cu–Ni composite.

3.3. Interface characteristic and fracture surface of C/Cu–Ni composites

By contrast with the C/Cu–Fe composites, there is no chemical reaction between the carbon fibre and nickel during the composite fabrication process ($\Delta G_{Ni_3C} > 0$ at 800 °C) and no obvious boundary between interface zone and the carbon fibre (Fig. 4a). The Cu–Ni duplex coating is converted to a non-brittle, face-centred cubic (f.c.c.), Cu–Ni solid solution during the hot-press process [8], which is able to dissolve minute amounts of carbon fibre causing continuous transition from carbon fibre to interface zone. The length of the fibre pullout is much shorter than that for the C/Cu-composite (Fig. 4b). The matrix emerges as an obvious plastic deformation on the fracture surface to indicate that the interface and matrix of the composites have retained good plasticity (Fig. 4c).

Fibre, metal matrix and their interface, the three components of fibre reinforced metal matrix composites, take different rôles in the loading process of composites. Fracture characteristics of composites depends not only on the mechanical properties of fibre and matrix but also on interfacial strength, interfacial brittleness and brittle zone thickness.

Considering the case when no chemical reaction takes place at the interface and interface keeps good plasticity so as not to form any cracks during fracture process, then, even so, owing to the brittleness of carbon fibre, cracks form first in carbon fibre. The propagation model for cracks formed in carbon fibres depends on interfacial strength. If this is extremely weak, for example in the C/Cu composites interface, then under the stress concentration at the fibre-matrix interface, the crack propagates along the fibre surface to make the matrix detach from fibre until the stress concentration at the interface relaxes. The fibre is pulled out in long lengths; the strength of composites in this case is relatively low. If the interface is too strong to debond during the composite loading process, the crack formed in the carbon fibre is not able to divert along the fibre–matrix interface, but instead propagates across the fibre until brittle fracture of the composite. In this case, the carbon fibre cannot be pulled out. In the above two extreme conditions, the reinforcing ability of the carbon fibre is not able to be maximised for advantage. Good strength of C/Cu composites is obtained by an appropriate increase in interfacial strength, for example, high flexural strength of C/Cu–Ni composites is gained by an increase in interfacial strength provided from the dissolution of Cu–Ni solid solution to carbon fibre at the interface.

When chemical reactions take place at the interface, the formation of the reaction zone, which is brittle in general, can facilitate strong bonding and cause a stress concentration on the fibre surface. Theoretical work has been carried out to predict and characterize the influence of the brittle zone thickness on strength and fracture strain by Ochiai and Murakami [9]. Mechanical properties of composites as a function of the brittle zone thickness, as predicted by this model, is illustrated graphically in Fig. 5. At the brittle zone, below a critical thickness, C_B, the effect of the intrinsic defects in the fibre is stronger than that of the newly formed notch. The fibre is able to maintain its own full strength and the composite strength is controlled by these defects. When the thickness of the brittle zone is greater than C_B, the fibre is able to deform after the formation of the notch until the stress level is favourable for the notch to be extended. The strength of fibre decreases with increasing thickness of the brittle zone. C_B for different reinforcements is different; it is 0.17 μm

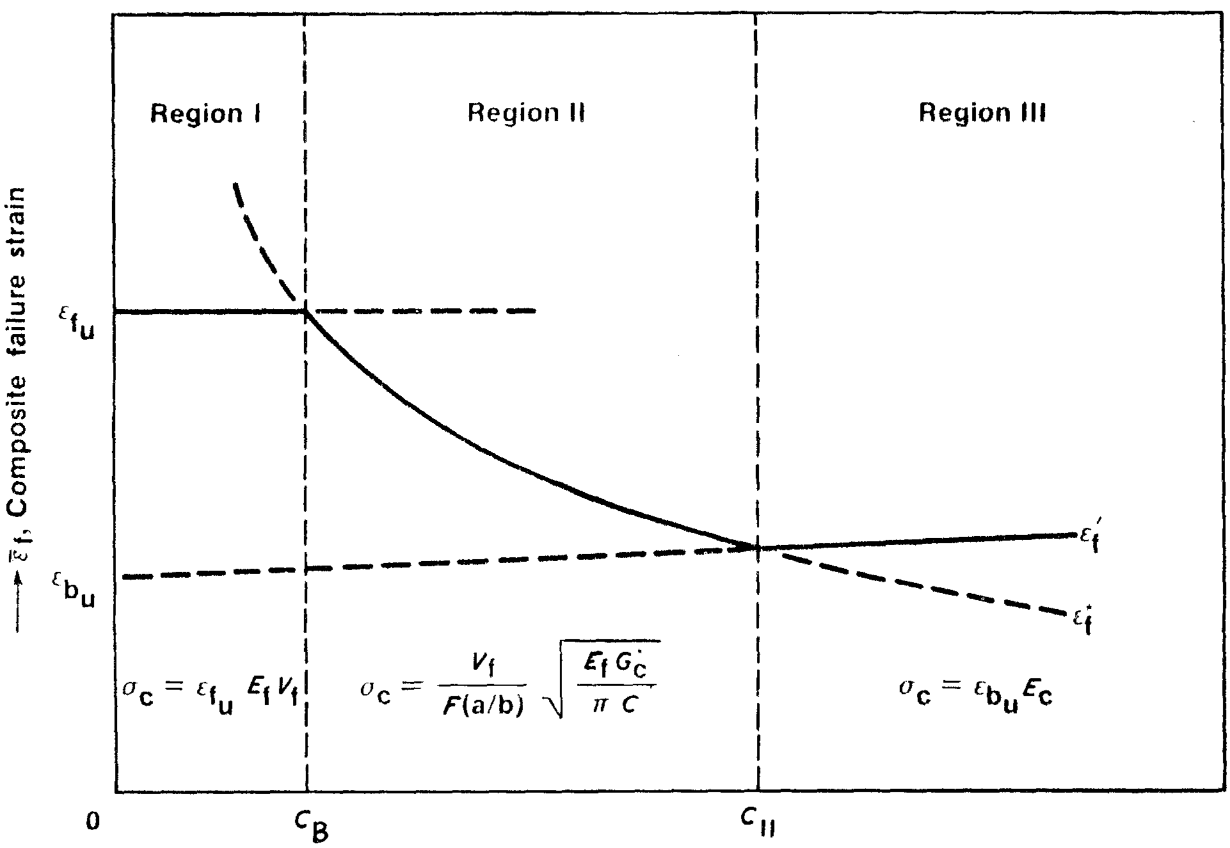

Figure 5 Plot illustrating the influence of the brittle zone thickness on the properties of composites from Reference 9.

for a carbon fibre [10]. In this paper, the thickness of the interfacial reaction zone in the C/Cu–Fe composite is about 0.1 μm smaller than the C_B of the carbon fibre. Such an interface has no negative effect on the carbon fibre but has a positive contribution to mechanical properties of the composite.

For an extremely weak interface bonding, such as C/Cu composites, raising the interfacial strength is an important approach to increasing the mechanical property of the composite. Increasing interfacial strength is generally carried out in two ways: 1. making fibre react with the matrix. Here the interface is strengthened by the pinning force of particles formed on the fibre surface; and 2. making the matrix dissolve the carbon fibre. Here the interface is strengthened by the dissolution zone. However, if the extent of interaction (chemical reaction and dissolution) at the interface is not controlled, then the carbon fibre will be degraded with subsequent loss in strength. The application of an "inert metal–active metal" duplex coating on carbon fibre will reduce this problem. The inert metal (internal Cu layer in this paper) will neither react with nor dissolve carbon fibre; the active metal (external Fe and Ni coating in this paper) must have a certain solubility in the inert metal but does not react with the inert metal to form a brittle intermetallic compound and is able to diffuse through the inert metal to the surface of the fibre in order to react with or dissolve the fibre. On the other hand, the thickness of the inert metal layer is able to adjust the concentration of the active metal on the fibre surface to control the extent of the reaction and dissolution at the interface. Thus, it is able to not only increase the interfacial strength but also it keeps the characteristic of the fibre through application of the duplex coating.

4. Conclusions

1. One main approach to increasing the flexural strength is to provide an adequately strong interface for the extremely weak interface of C/Cu composites. Raising the interfacial strength causes the length of fibre pullout to lessen and the brittleness of composite increases during the composite fracture process.

2. Carbon fibre–copper matrix interfaces in C/Cu–Fe and C/Cu–Ni composites are characterized by a discrete layer of polycrystalline Fe_3C particles and a continuous layer of f.c.c. Cu–Ni solid solution, respectively. Interfaces of C/Cu–Fe and C/Cu–Ni composites are strengthened by the reaction between Fe and carbon fibre and dissolution of Cu–Ni solid solution to carbon fibre, respectively.

3. The application of the "inert metal–active metal" duplex coating on the fibre surface not only increases the interfacial strength but also it keeps a high strength characteristic for the carbon fibre.

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