Copper alloy/Carbon heat sink composite materials elaborated by a powder metallurgy process

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SUMMARY

Copper alloy/Carbon fibre composites have been developed to propose high efficiency heat sinks. Annealing treatments are performed to create a strong interface (carbide) and allow a good transfer of properties between the Copper alloy matrix and the Carbon fibres. The final composite is characterised in term of thermal, mechanical, microstructural and chemical analyses.

Keywords: Heat sink, Thermal Conductivity, Coefficient of thermal expansion, Metal Matrix Composite, Carbon fibre, Copper alloys, Nanoindentation.

INTRODUCTION

In the field of power electronics, thermal management of silicon chips plays a key role in our ability to increase their performance. It is necessary to dissipate the excess of heat in order to prevent heating and consequent deterioration of silicon chips.

Multichip modules are composed of different layers between silicon chip and heat sink (Figure 1). Heat generated by the electronic components is dissipated through the heat sink, generally made of Copper that is brazed on to a DBC substrate (Copper - Ceramic - Copper). The material system of choice should not only have very good thermal dissipation, but the reliability is greatly limited by the critical difference between the coefficients of thermal expansion (CTE) of the Copper ($17.\ 10^{-6}\ K^{-1}$) and that of ceramic (mainly Alumina) substrate ($8.\ 10^{-6}\ K^{-1}$) [1].

Consequently, there is a strong need for the development of novel Metal Matrix Composite (MMC) materials having a low coefficient of thermal expansion (CTE) combined with high thermal conductivity in order to replace Copper.

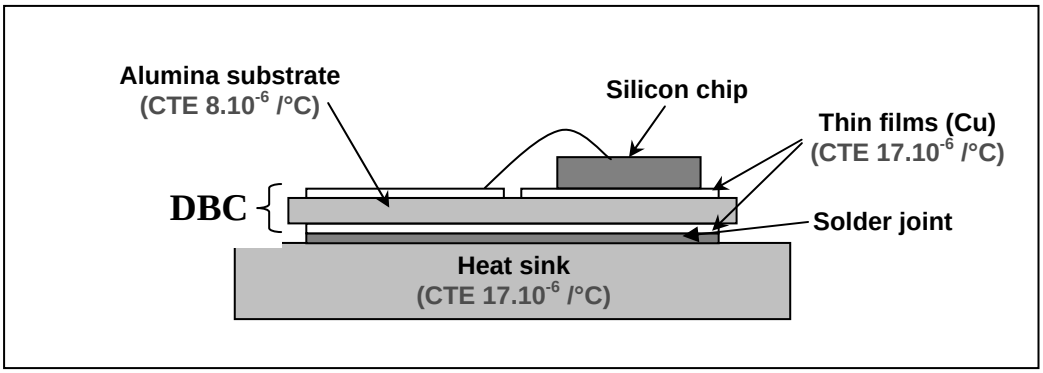

Figure 1: Schematic picture of a typical multichip module [1]

Carbon fibre reinforced copper matrix composites offer a good compromise between thermo-mechanical properties and high conductivity [2]. Their advantages are 1) lower density than copper, 2) very good TC, 3) low CTE and 4) good machinability. General mechanical and/or physical properties of MMCs are linked with the properties of the matrix, the reinforcement and the interfacial zones. Since Copper and Carbon in Cu-C composites are chemically inert, Chromium or Boron are added to Copper to promote chemical reaction which will allow, after optimised annealing treatment, a good transfer of properties [3][4].

PREPARATION AND CHARCTERISATION OF COMPOSITE MATERIAL

Processing of the composite

Chromium or Boron have been chosen as additive element to the Copper matrix because these elements are supposed to react with Carbon to form carbide compound (negative Gibbs energy).The Copper base alloys are Cu-B (0.05 wt. % of B) and Cu-Cr (0.63 wt. % of Cr). The powders are prepared by CERAM (United Kingdom), by an atomisation process, with a particle size under 25 µm. Several kinds of chopped carbon fibres are used, with a diameter ranging from 9 to 10 µm, a length around 100 µm and different thermal properties. These fibres, manufactured by Nippon Graphite Fibre Corporation, named CN80C and XN100 (Figure 2), present an axial thermal conductivity of 320 $W.m^{-1}.K^{-1}$ and 900 $W.m^{-1}.K^{-1}$ respectively and an axial CTE of -1. 10^{-6} K^{-1}.

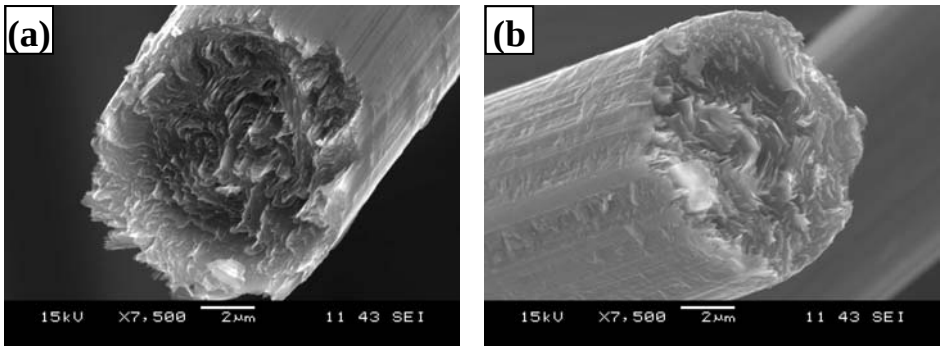

Figure 2: SEM micrographs of Carbon fibres (a) CN80C and (b) XN100.

Copper alloy powders are mechanically mixed with carbon fibres (volume fraction equal to 30 %) and are then hot pressed at 950ºC under 50 MPa during 20 minutes to obtain dense materials. In the furnace, a reducing atmosphere of Argon/Hydrogen (5 vol. %) prevents the oxidation of the copper powder during the sintering cycle. Optimised annealing treatments are then performed (1000°C, 24h, under reducing atmosphere) to achieve strong carbide interfaces.

Characterisations

Thermal conductivity and coefficient of thermal expansion have been measured using laser flash technique (Netzsch LFA 457) and dilatometry (Netzsch DIL 402C, horizontal dilatometer). Interface microstructure and chemistry of composite samples have been analysed using Transmission Electron Microscopy (TEM), Scanning Electron microscopy (SEM), Auger Electron Spectroscopy and Electron Probe MicroAnalyses (EPMA) techniques. Mechanical properties have been measured using nanoindentation technique (Hysitron Inc., Bio Ubi VII) in order to relate the mechanical properties of the composite material to its interfacial chemistry and microstructure.

RESULTS AND DISCUSSION

EPMA analyses of Cu-Cr/C and Cu-B/C composite materials have been performed in order to characterise the distribution of the alloying element which respect to the Copper/Carbon interface as a function of the annealing treatment. Figure 3a shows Carbon and Chromium distribution before annealing treatment. Some Chromium has already diffused at the Copper/Carbon interface during the densification process, but a large quantity of Chromium is still present inside the Copper matrix. After annealing treatment, figure 3b clearly shows that the Copper matrix is almost free of Chromium which has diffused toward the Copper/Carbon interface.

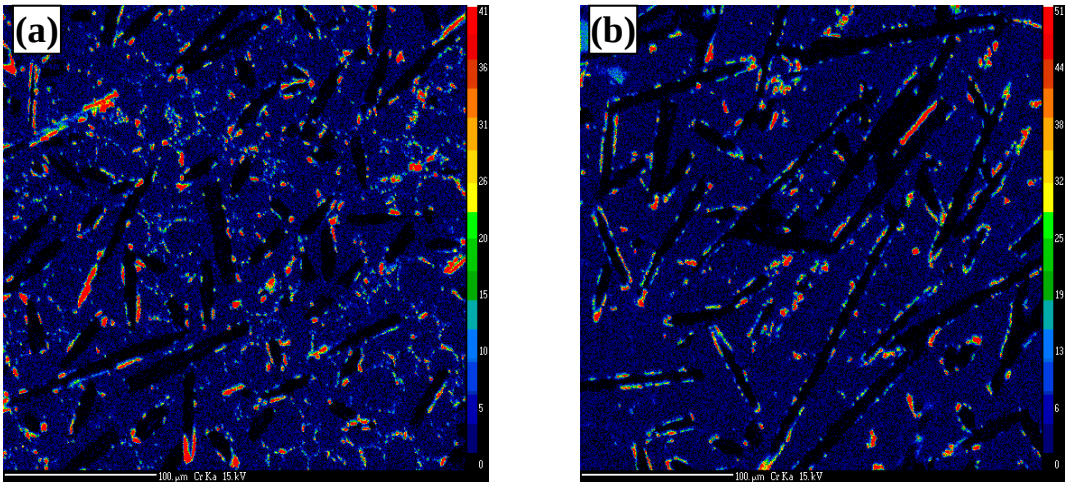

Figure 3: EPMA mapping of Chromium in Copper-Chromium/Carbon fibre composite (a) before and (b) after annealing treatment at 1000°C/24h.

This phenomenon can also be observed by SEM using back scattered electron imaging (Figure 4). At that magnification, another phase, which could be attributed to Chromium carbide, is observed around the Carbon fibre. This observation clearly shows that the carbide distribution or its thickness is not uniform around Carbon fibre. We observe similar effects on Cu-B/Carbon fibre material.

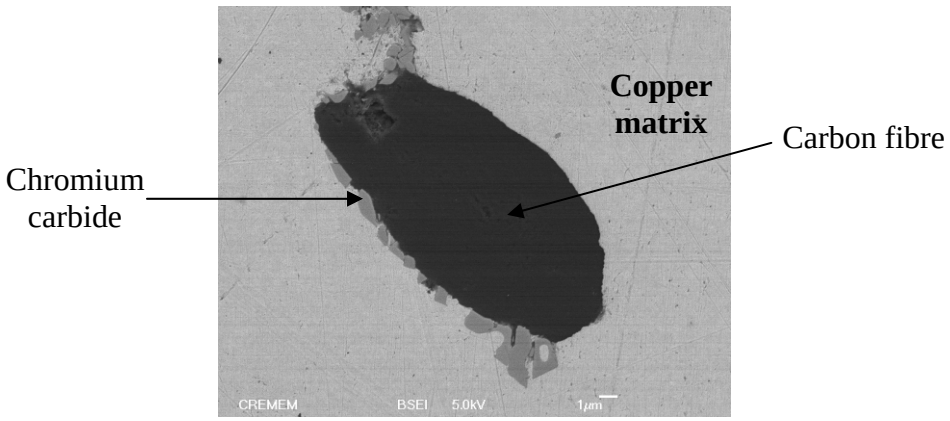

Figure 4: Micrography SEM of Copper Chromium / Carbon fibres composite after annealing treatment 1000°C/24h under controlled atmosphere.

TEM analyses have been performed on the same composite materials (Figure 5). The thickness of the carbide interphase has been highlighted (interphase zone thickness ranges from 50 nm to a micron) and diffraction patterns clearly show the formation of the different carbide (Cr_3C_2 for Cu-Cr/C composite materials and B_4C for Cu-B/C composite materials).

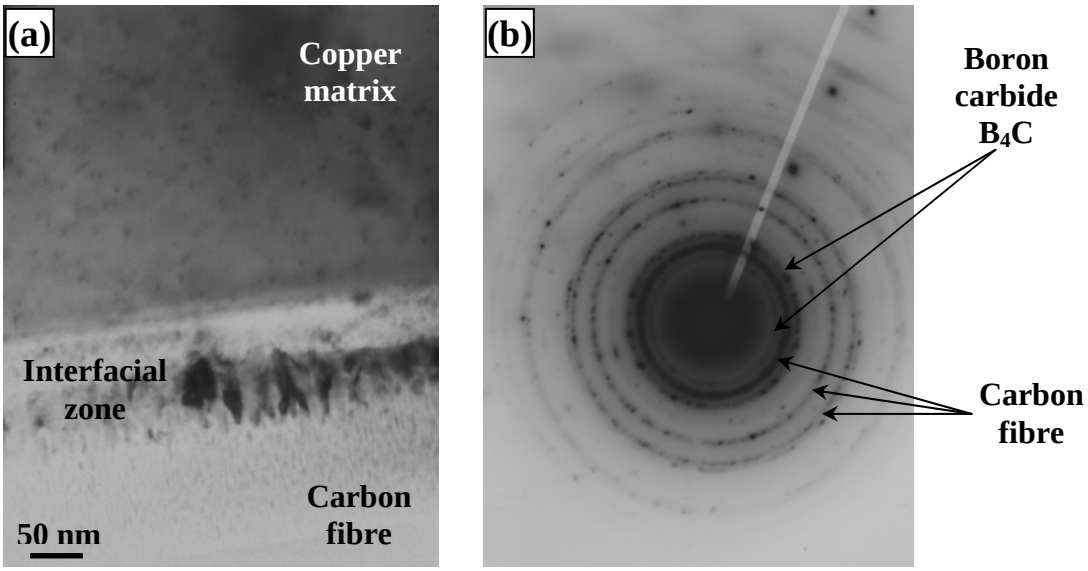

Figure 5: (a) TEM micrographs of Cu-B/C composite and (b) diffraction pattern performed at the interfacial zone

Nanoindentation measurements have been performed on Cu-Cr/C composite material in order to determine hardness and elastic modulus on different regions of the material (matrix, reinforcement and interface). Figure 6 shows the evolution of nanoindentation Load-Depth profiles on these three zones. Three curves shapes have been obtained. Hardness and elastic modulus have been calculated from these curves (Table 1). These results show an increase of elastic modulus and hardness at the interfacial zone which correspond well to the carbide presence at the interface.

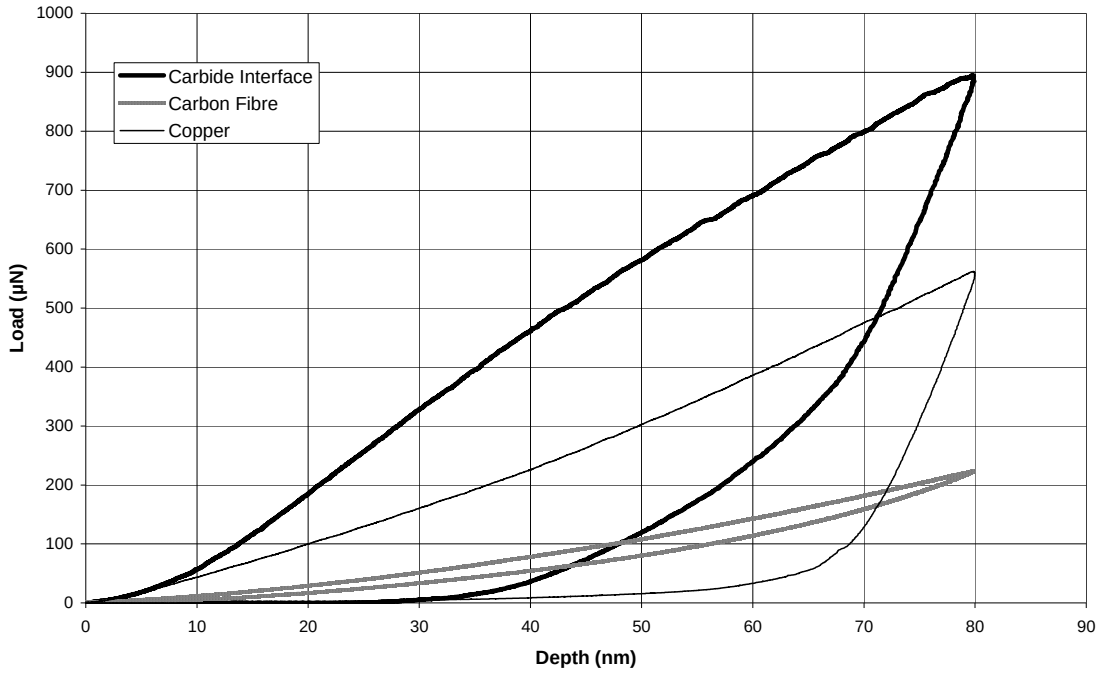

Figure 6: Nanoindentation Load-Depth profile of Copper, Carbon fibre and Chromium carbide interface.

Table 1: Elastic modulus and hardness of Carbon fibre, Copper matrix and interface.

	Carbon fibre	Copper matrix	Interface
Elastic modulus (GPa)	16	115	120
Hardness (GPa)	2.2	3.2	5.5

Finally, the coefficient of thermal expansion has been measured before and after annealing treatment at 1000°C/24h under controlled atmosphere. A 25% decrease of the CTE is observed after annealing treatment (from 16 10^{-6} K^{-1} to 12 10^{-6} K^{-1}). The thermo-mechanical properties of the composite is clearly improved in relation with the formation of the carbide compound at the Copper/Carbon fibre interfaces.

Conclusion

Copper alloy/Carbon fibre composite materials have been elaborated and annealed in order to create chemical bonding (carbide) at the interface zone between Copper and Carbon fibre. Nanoindentation and CTE measurements of the non annealed and annealed composite materials agrees well with the chemical and microstructural analysis of their interfacial zones that shows that strong carbide interphase (Cr_3C_2 for Cu-Cr/C and B_4C for Cu-B/C) is formed. As expected, such a strong bonding improves the thermal and mechanical properties of the Cu-Cr/C and Cu-B/C composite materials.

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