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Preparation by tape casting and hot pressing of copper carbon composites films

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Abstract

During this last decade, the use of metal matrix composites (MMCs) such as AlSiC or CuW for heat dissipation in microelectronic devices has been leading to the improvement of the reliability of electronic power modules. Today, the continuous increasing complexity, miniaturization and density of components in modern devices requires new heat dissipating films with high thermal conductivity, low coefficient of thermal expansion (CTE), and good machinability. This article presents the original use of copper carbon composites, made by tape casting and hot pressing, as heat dissipation materials. The tape casting process and the sintering have been adapted and optimised to obtain near fully dense, flat and homogeneous Cu/C composites.

A good electrical contact between carbon fibres and copper matrix and a low porosity at matrix/copper interfaces allow obtaining a low electrical resistivity of 3.8 $\mu\Omega\,\mathrm{cm}^{-1}$ for 35 vol.% carbon fibre (electrical resistivity of copper = 1.7 $\mu\Omega\,\mathrm{cm}^{-1}$). The CTE and the thermal conductivity are strongly anisotropic due to the preferential orientation of carbon fibres in the plan of laminated sheets. Values in the parallel plan are, respectively, $9 \times 10^{-6}\,{}^{\circ}\mathrm{C}^{-1}$ and 160–210 $\mathrm{W\,m^{-1}\,K^{-1}}$ for 40 vol.% fibres. These CTE and thermal conductivity values are in agreement with the thermo-elastic Kerner's model and with the Hashin and Shtrikman model, respectively.

Keywords: Tape casting; Composites; Thermal expansion; Thermal conductivity; Carbon fibre; Cu; Films

1. Introduction

In modern electronic devices, the packaged structures consist of a variety of metallic, ceramic, plastic or composite components. The large difference of coefficient of thermal expansion (CTE) between ceramic substrates, such as Al_2O_3 and AlN, heat dissipation materials, such as Cu and Al, and Si and GaAs semiconductors, induces thermal stresses resulting in failures at the interfaces between the different layers of the devices. In high power dissipation packages, thermal management is an important issue to prevent thermal damage of sensitive components on the silicon ship, particularly for high-density electronic packaging. Thermal management is thus one critical aspect in design of multichip modules to ensure reliability of electronic devices with high packing and power densities. In this context, there is an increasing demand of new heat dissipation materials having low coefficient of thermal expansion combined with high thermal conductivity.

Aluminium and copper are good candidate materials for the heat dissipation due to their thermal conductivity, but they have high values of CTE. Materials with low CTE and high thermal conductivity, such as Al/SiC or Cu/W composites, have improved the reliability of electronic devices.[1] However, these composites are often too expensive for many applications. In addition, their machinability and the elaboration of thin sheets remain still very difficult.

Carbon fibres reinforced copper matrix composites offer a good compromise between thermo mechanical properties and thermal conductivity.[2] Their advantages are (i) lower density than copper, (ii) very good thermal conductivity, (iii) low coefficient of thermal expansion, and (iv) good machinability (Table 1). Other advantages of copper/carbon fibre composites

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Table 1
Properties of different materials used in electronic devices

Function	Materials	CTE $10^{-6}\,°C^{-1}$ (RT-200 °C)	Thermal conductivity ($W\,m^{-1}\,K^{-1}$ (25 °C))	Density ($g\,cm^{-3}$)
Chips	Si	4.2	150	2.3
	GaAs	5.9	45	5.32
Heat sinks	Copper	17	400	8.95
	Aluminium	23	230	2.7
	Aluminium/63 % SiC	8	165	3
	Copper/85 % W	6	180	17
	Copper/40% Carbon fibers (Pitch)	$17\perp, 9\parallel$	$160\perp, 210\parallel$	6.11
Substrates	Al_2O_3	6.7	20–35	3.9
	AlN	4.5	170–250	3.26

are adaptive thermal properties which can be adjusted with the nature and the volume ratio of carbon fibres. During last decades, several processes have been developed to elaborate copper carbon composites through hot pressing or squeeze casting.[3,4] However, all processes are difficultly perfecting and too expensive for elaboration of thin sheet materials.

Tape casting process offers an original solution for the elaboration of thin sheets of metal matrix composites[5,6] or, in our case, carbon fibre reinforced copper matrix composites. This process is based on powder metallurgy technology that offers many advantages such as the decrease of the machining cost (economical aspect) and of power consummation (environmental aspect). Tape casting process is currently used on the large scale to produce thin ceramic or multilayer structures of various materials for different applications,[7] such as Al_2O_3 and AlN substrates for electronic devices, $BaTiO_3$ for multilayer capacitors, solid electrolytes for sensors or energy conversion, piezoelectric ceramics for actuators or transducers. The main characteristics of this process are low cost, accurate control of the thickness from 25 to 1000 μm, good surface finish and high quality of laminated materials.[8] The present paper aims to evaluate the feasibility of tape casting process for the elaboration of the copper/carbon composite sheets with thicknesses ranging from 100 to 500 μm.

2. Experimental procedure

Tape casting process (Fig. 1) consists of the preparation of a suspension of the inorganic powder(s) in an aqueous or non-aqueous system. This slurry is a complex multicomponent system typically containing the following components: powder (ceramic and/or metallic), solvent, dispersant, binder, and plasticizer. The suspension must be stable, homogeneous and with a suitable rheological behaviour according to the tape casting process. The slurry is spread onto a support by means of a moving doctor blade. After evaporation of the solvent, the obtained dried tape, or green tape, was cut to the desired shape.

2.1. Starting metallic and ceramic powders

Copper powders from Eckart Poudmet, Germany, and carbon fibres pitch type from Misubishi Chemical, Japan, that have a better thermal conductivity than PAN (PolyAcryloNitrile) fibres,

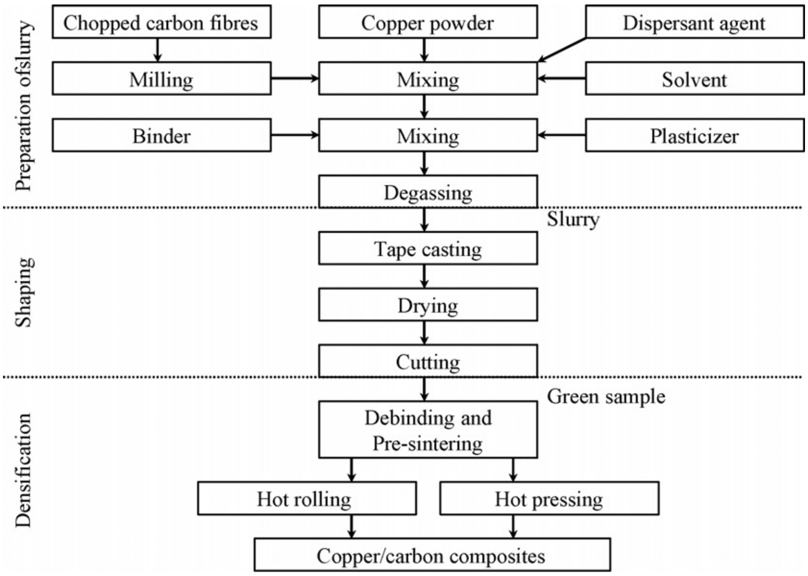

Fig. 1. Processing flow sheet of carbon reinforced copper matrix composites.

Table 2
Main characteristics of starting materials

Materials	Specific surface area ($m^2\ g^{-1}$)	Mean particle diameter (μm)	Density ($g\ cm^{-3}$)	CTE (10^{-6}/°C)	Thermal conductivity ($W\ m^{-1}\ K^{-1}$)	Young's modulus (GPa)
Copper	0.5	28	8.9	17	400	120
Carbon fibre	0.21	10	2.12	$-1.2 \parallel$	$5 \perp, 140 \parallel$	$20 \perp, 640 \parallel$

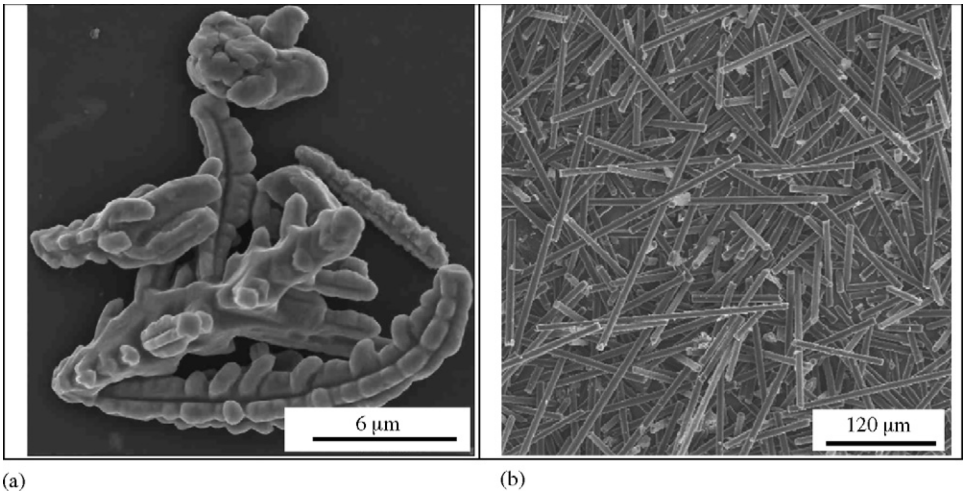

Fig. 2. SEM micrographs of (a) the copper powder and (b) the milled carbon fibers.

are used. The main physical characteristics of powders are given in Table 2.

Scanning electron microscopy (SEM) and laser granulometer characterizations have shown that copper particles have dendrite shape with a range size from 25 to 30 μm (Fig. 2a). Starting chopped carbon fibres have diameter ranging from 9 to 10 μm and mean length of 6 mm. After milling, using planetary mill in alumina jar and alumina balls, the mean length of carbon fibres is decreasing down to 100 to 200 μm (Fig. 2b). In fact, for carbon fibre length greater than 200 μm, the flowability of slurry decreases strongly leading to the impossibility of slurry casted thin film.

2.2. Choice of organic components for tape casting

The solvent must wet the carbon fibres and copper powder and should have a low temperature of vaporization. Also, powders must be chemically stable in the solvent. Taking into account these requirements, the solvent chosen is the azeotropic mixture of ethanol and 2-butanone (40/60). Indeed, it offers a low boiling point (74.8 °C) and a low dielectric constant that is favourable for a good wettability of carbon fibre.[9] The nature of the solvent and of the powder will determine the following choice of organic additives, such as dispersant, binder and plasticizer.[10]

Several dispersants able to develop repulsive forces between particles in a low polar solvent, generally by electrosteric mechanisms, have been tested using sedimentation test in a first screening and then, using rheological measurements with a rotational viscometer (Table 3). According to sedimentation tests in the azeotropic mixture of ethanol/2-butanone (40/60), one phosphate ester (CP213, Cerampilot, France) has lead to the best desagglomeration and dispersion of copper and carbon particles. The optimum concentration of phosphate ester was determined by rheological measurements (Fig. 3). The minimum viscosity, then the best state of dispersion, was obtained for a dispersant concentration of 0.5 wt.% on the dry powders basis.

Table 3
The different dispersants tested

Dispersant	Suppliers	Chemical nature
Duomeen TDO	Akzo Nobel (France)	Dioleate propylenediamine
Phosphatan PR13T, PE 169		Phosphate ester
BYK 110	BYK Chemie (Germany)	Acetate methoxypropyl/alkylbenzene
Beycostat C213	Cerampilot (France)	Phosphate ester
Hypermer MT, KD1, KD2, KD	Uniqema (Belgium)	Polyamide polyester
Zephrym PD3315, PD7000		Polyoxyalkylene
Solsperse 20000, 22000 and 4000	Zeneca (Belgium)	Not identified

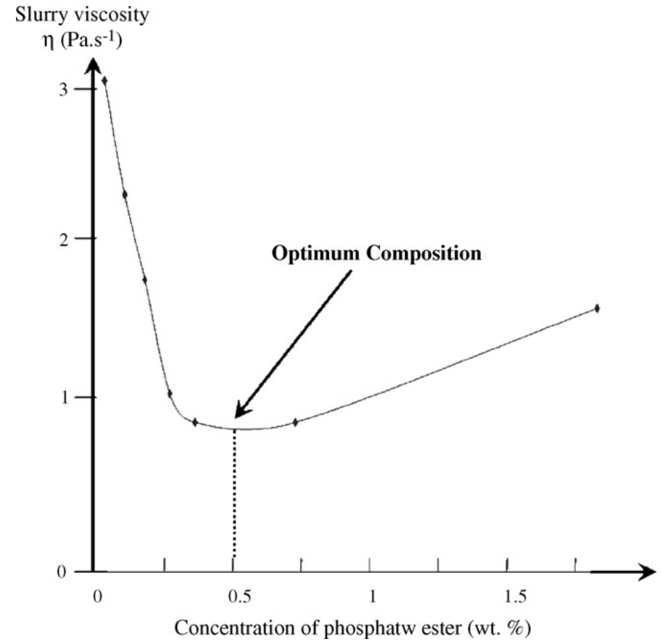

Fig. 3. Evolution of the viscosity of the slurry with the concentration of dispersant.

The binder ensures the cohesion of the green sheet to avoid cracking during drying and for handling. After evaporation, the binder molecules form organic bridges between copper particles and carbon fibres, resulting in high mechanical properties of the green tape.[11,12] The binder must be easily removed at low temperature without residues. The binder is a PolyMethyl MethAcrylate (PMMA) with a molecular weight ranging between 120,000 and 150,000 g mol^{-1} (Degalan 51/07, Degussa Hüls, Germany).

The plasticizer, which confers the flexibility to the green tape for easy handling, induces a decrease of the Tg of the organic phase. An efficient plasticizer of the PMMA is the Dibutyl phtalate with a low molecular weight of 300 g mol^{-1} (Sigma-Aldrich, France). A good compromise between the flexibility and the mechanical strength of the green tape was obtained for a binder/plasticizer ratio of 1.2.

2.3. Slurry preparation and tape casting

The tape casting suspension was prepared in two steps. The first one consists in dispersing, by planetary milling during 4 h, the copper powder and carbon chopped fibres in 2-butanone/EtOH solvent with phosphate ester as dispersant. The binder and the plasticizer were added to the suspension in a second step and the complete slurry was homogenised, also by planetary milling during 12 h, but at a lower rotating velocity. After homogenization, the slurry is degassed and directly casted onto a siliconed Mylar carrier film with a doctor blade. The doctor blade speed is fixed at 0.5 m min^{-1} with a gap of 0.5 mm, which corresponds to a shear rate of 10 s^{-1} and to a slurry viscosity of 1 Pa s (Fig. 4). The viscosity has been measured by CARRI-MED CSL 100 rheometer. The solvent evaporation was carried out at room temperature under air.

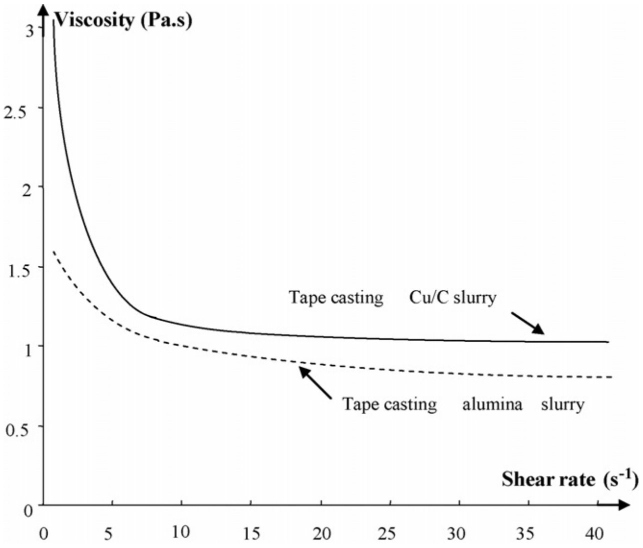

Fig. 4. Rheogram of the copper/carbon composite slurry and of a standard alumina tape casting slurry for comparison.

2.4. Green tape

The geometrical density of the green tapes varying from 2 to 2.5 g cm^{-3} corresponds to a relative density ranging from 0.55 to 0.65 of TD (theoretical density), that suggests a rather good arrangement of particles, whereas the particle shapes, like short fibre or dendrite copper particles, are not favourable to a good compaction. However, the carbon fibres are oriented in the casting plan due to shear imposed during tape casting (Fig. 5).

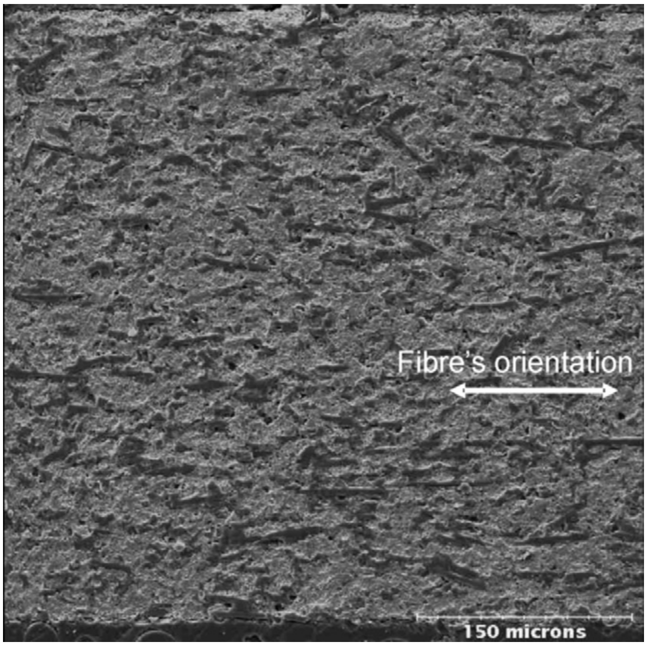

Fig. 5. SEM micrograph of a tape cast copper carbon composite film after debinding.

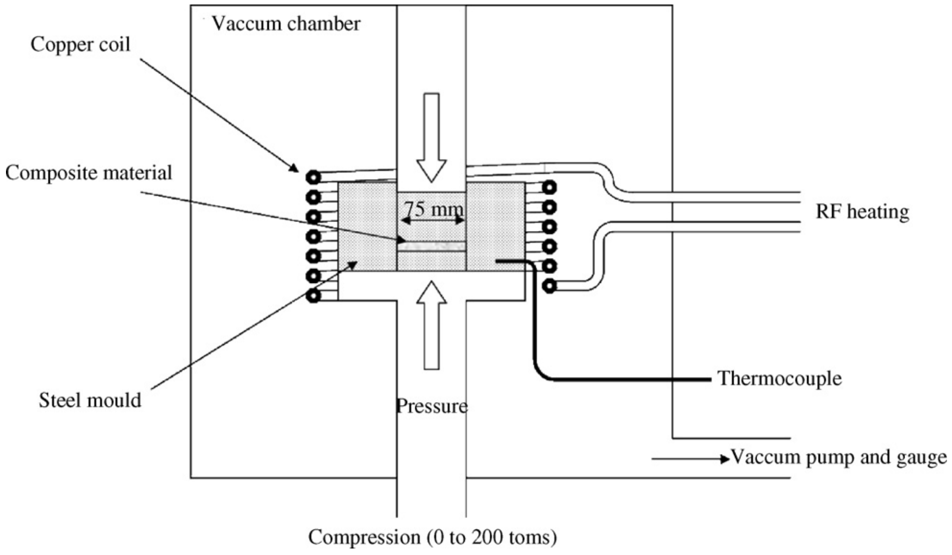

Fig. 6. Hot pressing device.

2.5. Thermal treatments

The organic components were removed during a thermal treatment at low temperature, i.e. debinding. The composites were then pre-sintering at higher temperature. The resulting composite structures have sufficient strength and flexibility for handling, but still present an important porosity. The thin sheets are then subsequently fully sintered by hot pressing (Fig. 6). In this densification step, 5 or 10 sheets (with thickness equal to 200 μm) can be pressed together for the elaboration of thick systems.

2.6. Debinding and pre-sintering

In the first step of firing, the organic additives, i.e. the binder, plastizicer and dispersant are burned out carefully. The removal of plasticizer and binder occurs, under air, between 120 and 350 °C, whereas the extraction, under nitrogen, is performed between 140 and 400 °C (Fig. 7).

Due to copper oxidation starting at 150 °C under air, debinding of copper/carbon composite green sheets were performed at 350 °C under nitrogen. In the second step of firing, the copper matrix was pre-sintered at 750 °C during 30 min in

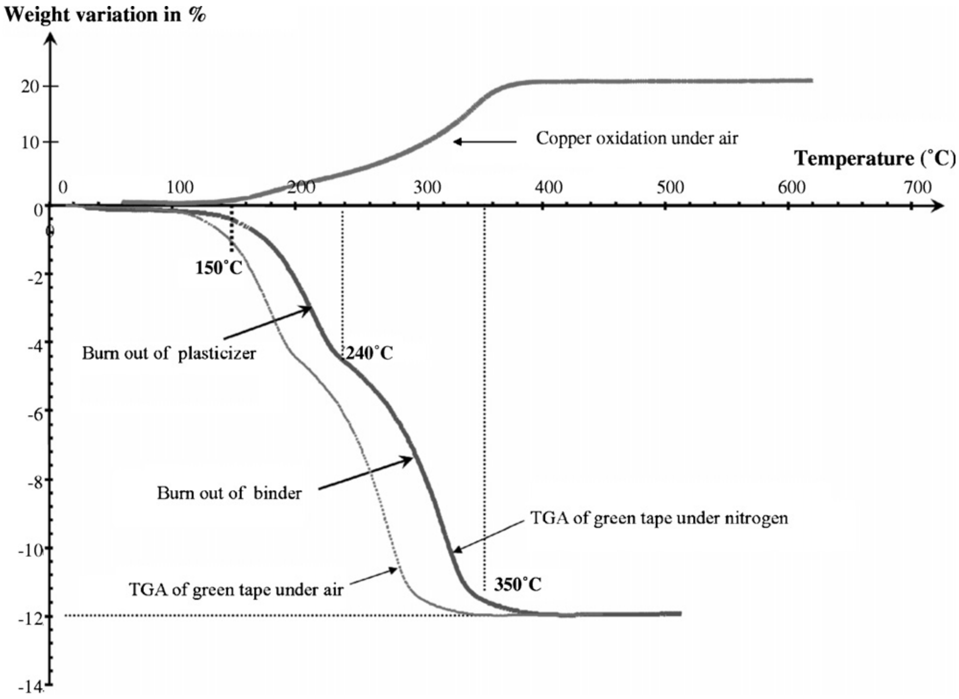

Fig. 7. TGA (2 °C min^{-1}) of a copper/carbon fibres green tape under air and nitrogen, and TGA of copper oxidation under air.

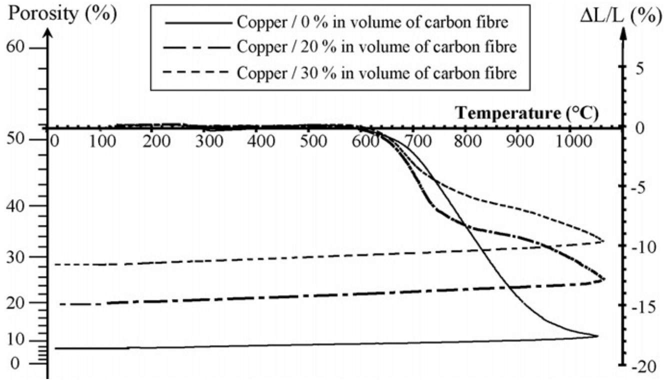

Fig. 8. Influence of carbon fiber concentration on the sintering of copper/carbon composites.

nitrogen. The resulting composite had a sufficient strength and flexibility for handling, but still presented an important porosity (20–30% in volume), which results from the presence of carbon fibres. Dilatometry curves demonstrate the influence of carbon on densification of copper/carbon composites (Fig. 8). The densification of the copper/carbon composites starts at about 600 °C. The first step of densification (600–700 °C) corresponds to the sintering of copper particles. Then, the densification rate is decreasing and remains roughly regular until 1000 °C. This second step of densification is due to the plastic strain of copper matrix at high temperature under the pressure of the dilatometer alumina rods.

The bad wettability of the carbon fibres by copper and the non-reactivity between carbon and copper led to the formation of a stable porosity between the copper matrix and the carbon fibres during the densification stage. Thus, the full densification of copper/carbon composites is not possible by conventional sintering. Hot pressing technique,[13,14] under controlled atmosphere, was finally used in order to obtain fully dense materials.

2.7. Densification by hot pressing

The pre-sintered individual tapes or multilayers were introduced between the 2 pistons of the steel mould which were heated, under vacuum (0.66 Pa), by induction system and regulation monitor. The samples were pressed under 50 MPa during 1 min at 650 °C with a heating rate of 25 °C min^{-1}. The temperature was controlled with a thermocouple placed into the steel mould.

2.8. Characterization

The electrical resistivity of composites was measured in the parallel plan of Cu/carbon fibre composites, on 20 mm × 5 mm × 0.5 mm sheet samples, using conventional 4 points method.

The thermal conductivity was measured by flash laser method in axial direction of small cylinders, typically 6–15 mm diameter and 2–5 mm high. The small cylinders were machined in specific multilayer samples (15–20 layers of 0.5 mm thickness each) in both parallel and perpendicular casting directions in order to measure the thermal conductivity in parallel and perpendicular directions of sheets.

The coefficient of thermal expansion was measured using a differential dilatometer (ADAMEL DI10, France) using a heating rate of 10 °C min^{-1} from room temperature to 250 °C under nitrogen. Tested samples consisted of laminates of 10 hot pressed films with a typical size of 50 mm × 50 mm × 5 mm.

3. Results and discussions

3.1. Densities and microstructures

Composite Cu/C materials with two different volume fractions of carbon fibre (30 and 40%) have been obtained. The density of both materials was identical with a relative density close to 99%. No specific degradation of the carbon fibre, induced by an eventual chemical reaction between Cu and C, was observed in agreement with the Cu-C phase diagram.

The Cu/C composites, observed by optical microscopy and SEM, showed a strong anisotropy microstructure between the perpendicular and parallel directions of the sheets (Fig. 9). The carbon fibres were mostly oriented in the casting plan due to: (i) shear imposed by the tape casting, and (ii) the hot pressing process. It could be expected that this orientation of carbon fibres lead to anisotropic properties, such as electrical resistivity, thermal conductivity and CTE.

3.2. Electrical resistivity

The electrical resistivity is increasing with carbon fibre content (Fig. 10). The experimental values are close to those predicted by inferior limit of Hashin and Shtrikman model,[15,16] taking $\rho_{\text{Cu}} = 1.7\ \mu\Omega\ \text{cm}^{-1}$ and $\rho_{\text{fibre}} = 1000\ \mu\Omega\ \text{cm}^{-1}$. These models have been described as follow:

Reuss's model,

$$\rho_{\text{composite}} = \frac{1}{(1 - V_{\text{f}}/\rho_{\text{m}}) + (V_{\text{f}}/\rho_{\text{f}})}$$

Superior limit of Hashin and Shtrikman model,

$$\varphi^{+}_{\text{composite}} = \rho_{\text{m}} + \frac{V_{\text{f}}}{(1/\rho_{\text{f}} - \rho_{\text{m}}) + (V_{\text{m}}/3\rho_{\text{m}})}$$

and Inferior limit of Hashon and Shtrikman model,

$$\rho^{-}_{\text{composite}} = \rho_{\text{p}} + \frac{V_{\text{m}}}{(1/\rho_{\text{m}} - \rho_{\text{f}}) + (V_{\text{f}}/3\rho_{\text{f}})}$$

where $\rho_{\text{composite}}$ is the electrical resistivity of composite, V_{m} the volume fraction of matrix, ρ_{m} the electrical resistivity of matrix, V_{f} the volume fraction of fibres, ρ_{f} the electrical resistivity of fibres.

This behaviour is linked to a good electrical contact between carbon fibres and copper matrix and to a low porosity at matrix/copper interfaces.

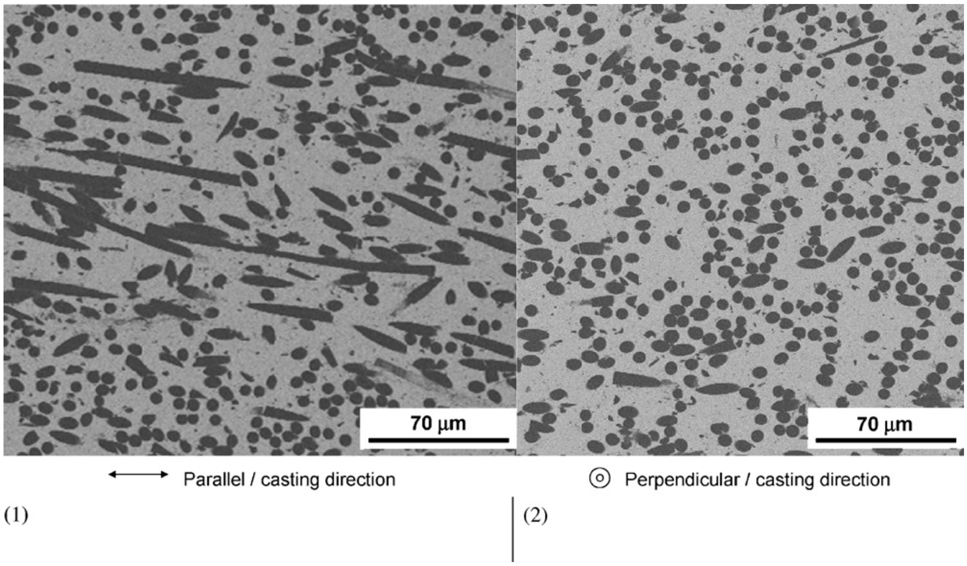

Fig. 9. SEM micrographs of hot pressed C/Cu films, (1) parallel plan/casting direction, (2) perpendicular plan/casting direction.

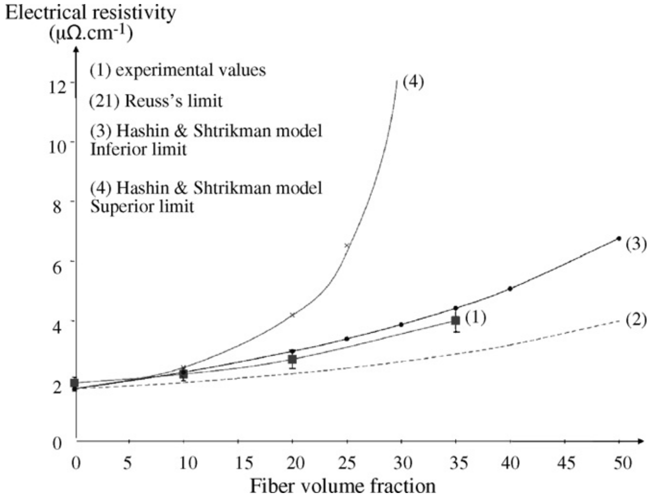

Fig. 10. Electrical resistivity of copper/carbon composites (parallel to the film surface).

3.3. Coefficient of thermal expansion

The Kerner's model is a thermo-elastic model generally used in CTE determination of composite materials (Table 4)[17,18]:

$$\alpha_{\text{composite}} = \alpha_m V_m + \alpha_f V_f + \frac{V_f(1 - V_f)(\alpha_f - \alpha_m)(E_f - E_m)}{E_m(1 - V_f) + E_f V_f + (3E_f E_m/4G_m)}$$

where $\alpha_{\text{composite}}$ is the CTE of composite, E_m the Bulk modulus of matrix, α_m the CTE of matrix, E_f the Bulk modulus of fibres, α_f the CTE of fibres; G_m the shear modulus of matrix; V_m the volume fraction of matrix, V_f the volume fraction of fibres.

Table 4 shows measured and calculated CTE values of Cu/C composite materials parallel (‖) and perpendicular (⊥) to the surface of the film. The calculated CTE has been calculated with carbon fibre CTE values in longitudinal direction ($\text{CTE}_{\parallel} = -1 \times 10^{-6}\,°\text{C}^{-1)}$ and in radial direction of fibre ($\text{CTE}_{\perp} = 12 \times 10^{-6}\,°\text{C}^{-1}$) and with copper value ($\text{CTE} = 17 \times 10^{-6}\,°\text{C}^{-1}$).

This model gives values quite close to experimental ones obtained for different volume fractions of fibre and fibre properties. However, the strong anisotropy of carbon fibre properties makes difficult to rightly estimate the mean CTE value of carbon fibres in plan of sheet (α_f), which is function of the distribution of orientation of the fibres. Also, the CTE measured in perpendicular direction of composite sheets is equal to $17 \times 10^{-6}\,°\text{C}^{-1}$ for the different volume fractions of fibres. However, the CTE is decreasing in the parallel direction of sheets and with the volume fraction of fibres down 12 and $9 \times 10^{-6}\,°\text{C}^{-1}$ for 30 and 40 vol.% carbon fibres, respectively.

3.4. Thermal conductivity

The thermal conductivity has been measured in the perpendicular and parallel directions of laminated sheets. Table 5 shows

Table 4
Measured and calculated CTE values of Cu/C composite materials parallel (‖) and perpendicular (⊥) to the surface of the film

	Volume of carbon fiber (%)	
	30	40
CTE (25–250 °C) ($10^{-6}\,°\text{C}^{-1}$)	‖ 12, ⊥ 17	‖ 9, ⊥ 17
CTE Kerner's model ($10^{-6}\,°\text{C}^{-1}$)	‖ 10.7 (with carbon fibrer CTE: ‖ -1×10^{-6}) ⊥ 15.2 (with carbon fibre CTE: ⊥ 12 $10^{-6}\,°\text{C}^{-1}$)	‖ 8.7 (with carbon fibre CTE: ‖ -1×10^{-6}) ⊥ 14.7 (with carbon fibrer CTE: ⊥ $12 \times 10^{-6}\,°\text{C}^{-1}$)

Table 5
Measured and calculated thermal conductivity values of Cu/C composite materials parallel (‖) and perpendicular (⊥) to the surface of the film

	Volume of carbon fiber (%)	
	30	40
Thermal conductivity ($W\,m^{-1}\,K^{-1}$)	‖ 250, ⊥ 170	‖ 210, ⊥ 150
Hashin and Shtrikman (superior limit in $W\,m^{-1}\,K^{-1}$)	‖ 277, ⊥ 246	‖ 242, ⊥ 203
Hashin and Shtrikman (inferior limit in $W\,m^{-1}\,K^{-1}$)	‖ 227, ⊥ 36	‖ 192, ⊥ 26

the measured and calculated thermal conductivity values of Cu/C composite materials parallel (‖) and perpendicular (⊥) to the surface of the film. The thermal conductivity has been calculated with medium thermal conductivity of carbon fibre: in casting plan (‖) equal to $70\,W\,m^{-1}\,K^{-1}$ and in radial direction of fibre (⊥) equal to $5\,W\,m^{-1}\,K^{-1}$ and with thermal conductivity of copper of $400\,W\,m^{-1}\,K^{-1}$.

The perpendicular direction corresponds to the unfavourable direction because of: (i) the carbon fibre orientation in the laminated sheets, and (ii) the probable thermal interfacial resistance between each sheet in the laminate. The parallel direction corresponds to the favourable direction because of the carbon fibre are oriented in casting plan or laminated sheet plan.

However, the measured values of perpendicular thermal conductivity are in the range of values calculated from Hashin and Shtrikman model.[15,16]

$$\lambda^{+}_{\text{composite}} = \lambda_{\text{m}} + \frac{V_{\text{f}}}{(1/\lambda_{\text{f}} - \lambda_{\text{m}}) + (V_{\text{m}}/3\lambda_{\text{m}})}$$

and

$$\lambda^{-}_{\text{composite}} = \lambda_{\text{p}} + \frac{V_{\text{m}}}{(1/\lambda_{\text{m}} - \lambda_{\text{f}}) + (V_{\text{f}}/3\lambda_{\text{f}})}$$

where $\lambda_{\text{composite}}$ is the thermal conductivity of composite, V_{m} the volume fraction of matrix, λ_{m} the thermal conductivity of matrix, V_{f} the volume fraction of fibres, λ_{f} the thermal conductivity of fibres.

In case of Cu/carbon fibre composites, the thermal conductivity is strongly anisotropic, with 150 and $170\,W\,m^{-1}\,K^{-1}$ in perpendicular direction, and 210 and $250\,W\,m^{-1}\,K^{-1}$ in parallel and perpendicular direction of multilayer samples for 40 and 30 vol.% fibres, respectively. The conductivity should be likely improved using new carbon fibres with a higher thermal conductivity.

4. Conclusions

Tape casting of thick films of copper carbon fibre composites seems promising to elaborate heat dissipation substrates for electronic applications allowing high packing and power densities. Whereas particles with a high shape factor, such as short fibre or dendrite copper particles used, are difficult to arrange, the optimisation of the dispersion and of the formulation of the tape casting slurry allow obtaining a green relative density of about 60%.

The formation, during sintering, of a stable porosity between the copper matrix and the carbon fibres, due to the bad wettability of the carbon fibres by copper and to the non-reactivity between carbon and copper, makes it necessary to use hot pressing in order to obtain fully dense materials (99%). No chemical reaction occurs between carbon fibre and copper matrix preventing from any degradation of the fibres.

Due to the orientation of carbon fibres in the plan of laminated sheets by the shear rate imposed during tape casting and by hot pressing, electrical resistivity, thermal conductivity and CTE properties are strongly anisotropic. The measured values of these physical characteristics, in the parallel plan of 40 vol.% carbon fibre/copper composites, i.e. $4\,\mu\Omega\,cm^{-1}$, $9 \times 10^{-6}\,°C^{-1}$ and $150–210\,W\,m^{-1}\,K^{-1}$ are promising for the elaboration of heat dissipation substrates.

The use of new fibres (nature, length, diameter, thermal conductivity) could be considered to improve properties of composites.

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References

1. Luedkte, A., Thermal management materials for high-performance applications. *Advan. Eng. Mater.*, 2004, **6**(3), 142–144.
2. Korb, G., Buchgrader, W. and Schubert, T., Thermophysical properties and microstructure of short carbon fibre reinforced Cu-matrix composites made by electroless copper coating or powder metallurgical route respectively, IEEE/CPMT Berlin, Int'l Electronics Manufacturing Technology Symposium, 27–28 April, 1998.
3. Praksan, K., Palaniappan, S. and Seshan, S., Thermal expansion characteristics of cast Cu based metal matrix composites. *Composites Part A*, 1997, **28**, 1019–1022.
4. Koráb, J., Stefánik, P., Kavecký, S., Sebo, P. and Korb, G., Thermal expansion of cross-ply and woven carbon fibre-copper matrix composites. *Composites Part A*, 2002, **33**, 133–136.
5. Corbin, S. F., Zhao-jie, X., Henien, H. and Apte, P. S., Functionally grated metal/ceramic composites by tape casting, lamination and infiltration. *Mater. Sci. Eng.*, 1999, 192–203.
6. Alcok, J. and Stephenson, D., Tape casting a flexible approach to surface engineering. *Mater. World*, 2000, 13–14.
7. Roosen, A., Basic requirements for tape casting of ceramic powders. *Ceram. Trans.*, 1998, **1**, 675–692.
8. Williams, J. C., *Doctor-Blade process, Treatise on Materials Science and Technology, Ceramic fabrication processes*, *vol 9*. Academic Press, New York, 1976, pp. 173–197.
9. Johnson, R. E., Morrison, J. and Morrison, W. H., Ceramic powder dispersion in nonaqueous systems. *Adv. Ceram.*, 1987, **21**, 173–197.
10. Moreno, R., The role of slip additives in tape-casting technology: Part I. Solvents and dispersants. *Am. Ceram. Soc. Bull.*, 1992, **71**(10), 1521–1530.
11. Böhnlein-Mauß, J., Sigmund, W., Wegner, G., Meyer, W. H., Heßel, F., Seitz, K. *et al.*, The function of polymers in the tape casting of alumina. *Advan. Mater.*, 1992(2), 73–81.
12. Moreno, R., The role of slip additives in tape-casting technology. Part II. Binders and plasticizers. *Am. Ceram. Soc. Bull.*, 1992, **71**(11), 1647–1657.

13. Evans, R. W. and McColvin, M., Hot forged copper powder compacts. *Powder Metall.*, 1976(4), 202–209.
14. Jha, A. K. and Kumar, S., Investigations into the high-speed forging of sintered copper powder strips. *J. Mater. Process. Technol.*, 1997, **71**, 394–401.
15. Hashin, Z. and Shtrikman, S., On some variational principles in anisotropic and nonhomogeneous elasticity. *J. Mechan. Phys. Solids*, 1962, **10**, 335–342.
16. Hashin, Z. and Shtrikman, S., A variational approach to the theory of the elastic behavior of multiphase elasticity. *J. Mechan. Phys. Solids*, 1963, **11**, 127–140.
17. Kerner, E. H., The elastic and thermo-elastic field of ellipsoidal inclusion and related problems. *Proc. R. Soc. Lond.*, 1957, **A421**, 376–396.
18. Tessier-Doyen, N. Etude expérimentale et Numérique du comportement thermomécanique de matériaux réfractaires modèles, Thesis, University of Limoges, 2003.