INFLUENCE OF VOLUME FRACTION AND ORIENTATION OF CARBON FIBRES ON HEAT TRANSFER IN UNIDIRECTIONAL COPPER MATRIX COMPOSITES

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In the paper results of heat propagation at original stages of heating of unidirectional copper-carbon fibre (Cu-CF) composite materials in dependence on volume amount of fibres in composite and on the direction of heat propagation concerning the fibre arrangement are summarised. Samples of Cu-CF composites containing 40, 52 and 63 vol.% fibres as well as pure aluminium and copper were heated in central region and the dependence of temperature on heating time in various places of the specimen was measured.

An increase of fibre amount in composite results in a decrease of its thermal conductivity which is manifested in the increase of the growth rate of temperature in composite. From the obtained dependences of heat propagation it follows that in unidirectional composites the heat propagates easier in the direction of fibres, and thus more expressive differences can be obtained in composite containing more than 50 vol.% of fibres.

K e y w o r d s: composite material, copper matrix, carbon fibre, heat transfer

VPLYV OBJEMOVÉHO MNOŽSTVA A ORIENTÁCIE UHLÍKOVÝCH VLÁKIEN NA PRENOS TEPLA V JEDNOSMERNÝCH KOMPOZITOCH S MEDENOU MATRICOU

V príspevku sú zhrnuté výsledky šírenia sa tepla v počiatočných štádiách ohrevu v jednosmerných kompozitných materiáloch meď-uhlíkové vlákno (Cu-CF) v závislosti od objemového množstva vlákien v kompozite a od smeru šírenia sa tepla vzhľadom na uloženie vlákien. Vzorky Cu-CF kompozitov s množstvom vlákien 40, 52 a 63 obj.% a čistý hliník a meď sa ohrievali v centrálnej oblasti a stanovila sa závislosť teploty od doby ohrievania na rôznych miestach vzorky.

So zvyšovaním množstva vlákien v kompozite klesá jeho tepelná vodivosť, čo sa prejavilo zvýšením rýchlosti narastania teploty v kompozite. Z nameraných závislostí šírenia

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sa tepla vyplýva, že pri jednosmerných kompozitoch sa teplo v smere uloženia vlákien šíri rýchlejšie, pričom výraznejšie rozdiely sa pozorujú pri kompozitoch obsahujúcich viac ako 50 obj.% vlákien.

1. Introduction

Metal matrix composites are frequently used as heat sinks in electronic devices. They are capable of providing higher temperature operating limits than their base metal counterparts, and they can be tailored to give improved strength, stiffness, thermal conductivity, abrasion resistance, creep resistance, and dimensional stability [1–5].

Today's electronic systems must dump large amounts of waste heat more effectively and balance the thermal stresses created by dissimilar materials. As power densities increase, reducing or eliminating thermal mismatch strains and improving the ability to dissipate heat will pose significant challenge for future electronic systems.

Copper and aluminium have a very high thermal conductivity (398 and 247 W/mK, respectively) and their coefficients of thermal expansion (CTE) are also high (17 ppm/K and 24 ppm/K, respectively). However, their CTEs can be brought down to 4 to 6 ppm/K by making composites containing appropriate volume fractions of low CTE materials such as silicon carbide, aluminiumnitride, or carbon [6, 7].

The materials covering a wide spectrum of substrate and heat sink packaging application requiring to match the thermal expansion coefficients of Si, GaAs, and Al_2O_3 are being manufactured from carbon fibre reinforced aluminium and copper composites [1].

Currently, a copper-carbon fibres (Cu-CF) composite with a CTE of cca 8 ppm/K is produced, but its thermal conductivity is only 175 W/mK. These materials are prepared by two main technologies – powder metallurgy and liquid metal infiltration of preform made of carbon fibres.

Matrix deposition processes in which the matrix is deposited on the fibre include electrochemical plating, plasma spraying, and physical vapour deposition. After deposition, a secondary step such as diffusion bonding is often needed to produce a component [6, 8].

However, carbon fibre (CF) reinforced composites have some serious limitations. Their thermal conductivity is highly anisotropic [9, 11]. An improvement in thermal conductivity in the direction normal to the fibre axis is critical for the heat-removal efficiency in the system. The ideal thermal management material for electronic application should have a high isotropic thermal conductivity. The composites have a low, reasonably acceptable CTE parallel to the fibre axis but their CTE normal to the fibre axis is very large, nearly equal to that of copper. During thermal cycling of the composites the compressive and tensile plastic deformations occurred. These limitations are predominantly due to the fibrous nature of the graphite fibre reinforcement. In effort to improve the thermal conductivity of such composites in the direction normal to the fibre by convenient combination of fibre arrangement in composite, by changing their volume fraction or including some high thermal conductive elements into the composites, it is important to know the heat transfer across the composite in dependence on the mentioned variables.

This paper describes an experimental characterisation of the heat transfer in the thin plate made of Cu-CF composite materials.

2. Experiment

The samples used in thermal conduction experiments were made of copper, aluminium, and unidirectional composites with volume fractions of fibres 0.40, 0.52, and 0.63. Cu-CF composites were made from Torayca T300 carbon fibre with 3000 monofilaments in tow. The fibres were coated by copper and the thickness of Cu coating gives volume of copper amount in composite. Composites were made by diffusion bonding of unidirectionally oriented fibres in vacuum at 600 ℃ [6, 10, 12].

To define thermal properties of composites, we used step heating method which is defined by limited duration of light pulse during the experiment is running. The light was generated by halogen lamp and aligned through glass bar which produced round light area of a diameter 10 mm (or square 7 × 7 mm using an aperture) in the centre of specimen of dimension 50 × 50 × 1 mm (Fig. 1). Propagation of heat was measured by thermocouples in various distances from the centre of specimen.

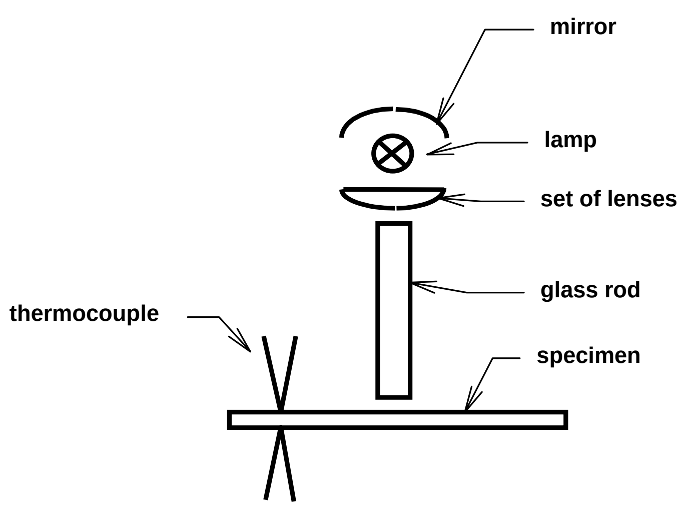

Fig. 1. A schematic view of an experimental setup.

Their location on exposed side is characterised using co-ordinate system $[x, y, z]$ where (x is parallel to fibre orientation, z is perpendicular to the surface of the sample) as $[0, 0, 0]$, $[15, 0, 0]$ and $[0, 15, 0]$, or on the opposite side $[0, 0, 1]$, $[15, 0, 1]$ and $[0, 15, 1]$.

Immediately after lighting the temperature increases, the temperature changes below 0.1 ℃ are registered and saved in personal computer. The method accuracy was tested on copper sample. The signals from several thermocouples located at the same distance from the middle of the light ring were recorded. Practically the same curves were obtained. In all experiments the starting temperature was 20 ℃, and heat was removed from plate to surrounding environment by combination of convection and radiation. Comparison of experimental and by method of finite elements calculated results gives the density of heat flux around 16000 W/m^2.

3. Results and discussion

Some of the heat sinks must absorb thermal energy from internal or external components during several seconds. Thus our work concerns the temperature change at the beginning of heat exposure. We assumed that removing of heat from surfaces to air with temperature of 20 ℃ is equal for all studied materials.

For bicomponent system the heat capacity of the composite c_c can be expressed by equation

$$c_\mathrm{c} = (1/\rho_\mathrm{c})(V_\mathrm{f}\rho_\mathrm{f}c_\mathrm{f} + V_\mathrm{m}\rho_\mathrm{m}c_\mathrm{m}), \tag{1}$$

where the density of the composite ρ_c is given by

$$\rho_\mathrm{c} = V_\mathrm{f}\rho_\mathrm{f} + V_\mathrm{m}\rho_\mathrm{m}, \tag{2}$$

where V is the volume fraction and f and m are symbols for fibre and matrix, respectively. Similarly, for thermal conductivity of the composite, λ_c, in direction parallel with fibres the following is valid:

$$\lambda_\mathrm{c} = V_\mathrm{f}\lambda_\mathrm{f} + V_\mathrm{m}\lambda_\mathrm{m}, \tag{3}$$

where λ_f and λ_m are thermal conductivities of fibres and matrix, respectively. Thermal diffusivity α of a material is given

$$\alpha = \lambda c^{-1}\rho^{-1}. \tag{4}$$

Some thermal properties of the studied material are in Table 1. Last two columns in Table 1 show thermal conductivity (taken from literature [10] for elements of technical purity and calculated after Eq. (3) for composites) and thermal

T a b l e 1. Thermal properties of studied materials

Material	Heat capacity $[\mathrm{J \cdot kg^{-1} \cdot K^{-1}}]$	Density $[\mathrm{kg \cdot m^{-3}}]$	$(c\rho) \times 10^{-6}$ $[\mathrm{J \cdot K^{-1} \cdot m^{-3}}]$	Thermal conductivity $[\mathrm{W \cdot m^{-1} \cdot K^{-1}}]$	Thermal diffusivity $[\mathrm{m^2 \cdot s^{-1}}] \times 10^6$
Al	896	2700	2.419	222.0	91.8
Cu	386	8930	3.447	380.0	110.2
CF–axial	758	1760	1.334	6.5	4.9
CF–radial	758	1760	1.334	0.8	0.6
Cu-40CF–parallel	429	6062	2.600	230.6	88.7
Cu-40CF–perpend.	429	6062	2.600	163.5	62.9
Cu-52CF–parallel	451	5202	2.346	185.8	79.2
Cu-52CF–perpend.	451	5202	2.346	120.7	51.4
Cu-63CF–parallel	479	4413	2.114	144.7	68.4
Cu-63CF–perpend.	479	4413	2.114	87.0	41.4

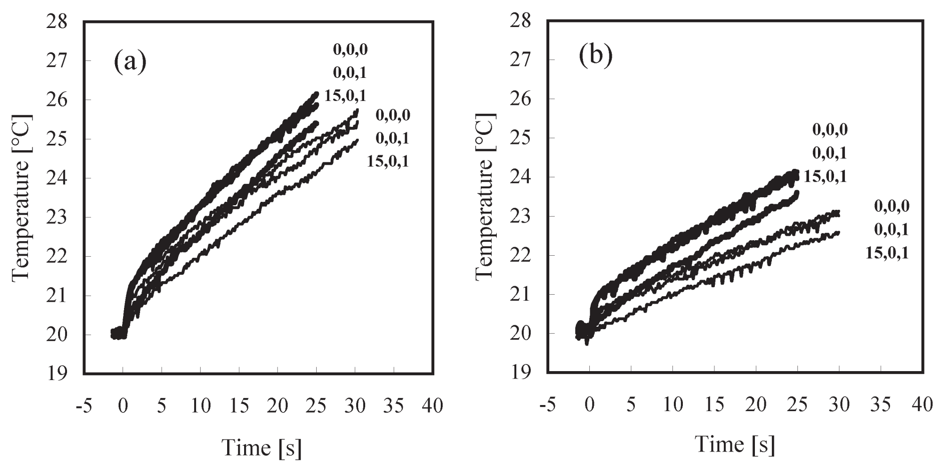

Fig. 2. Dependence of temperature on heating time for Al (a) and Cu (b) specimens. Upper (stronger) lines are for a round area of light, the lower ones are for a square heating area.

diffusivity using data for ρ, c, and λ from Table 1. There are two diffusivities for each volume amount of fibres; one is for fibre direction, the other is for the direction perpendicular to the fibres.

Figures 2a,b show the dependences of temperature on heating time for pure aluminium (a) and copper (b) measured in the centre of lighted area $[0, 0, 0]$ and at the distance of 15 mm from the centre in x [15, 0, 0] and y [0, 15, 0] axes. These measurements were done also on the back sides of the specimens – with co-ordinates [0, 0, 1], [15, 0, 1] and [0, 15, 1]. There are two sets (in Figs. 2a,b) of curves. The upper set (stronger lines) is for a round area of light, the lower set is for a square spot (1.6 times less than for round area). This gives a lower heat flux and due to it, the temperature increase is slower.

If radiant energy Q is instantaneously ($t = 0$) and uniformly absorbed in the small depth g at the front surface ($x = 0$), the temperature in the area $0 < x < g$ is given by [13]

$$T(x, 0) = \frac{Q}{\rho c g}, \tag{5}$$

where ρ is the density and c is the heat capacity.

Assuming that ratio Q/g is for both elements equal, product of density and heat capacity is for aluminium lower than for copper (see Table 1). From the relation (5) it results that the temperature at the front surface of aluminium is higher than that of copper (Figs. 2a,b). Temperature increase for both elements (Al and Cu) on the front [0, 0, 0] as well as rear [0, 0, 1] side is practically identical. This is due to high thermal diffusivity of both materials.

The variations between a temperature increase and heating time for unidirectional composites with three various volumes of fibres are in Figs. 3–5. In all cases the temperature increased with heating time. The rate of the temperature increase in the centre (co-ordinate [0, 0, 0]) as well as on the back side (co-ordinate [0, 0, 1])

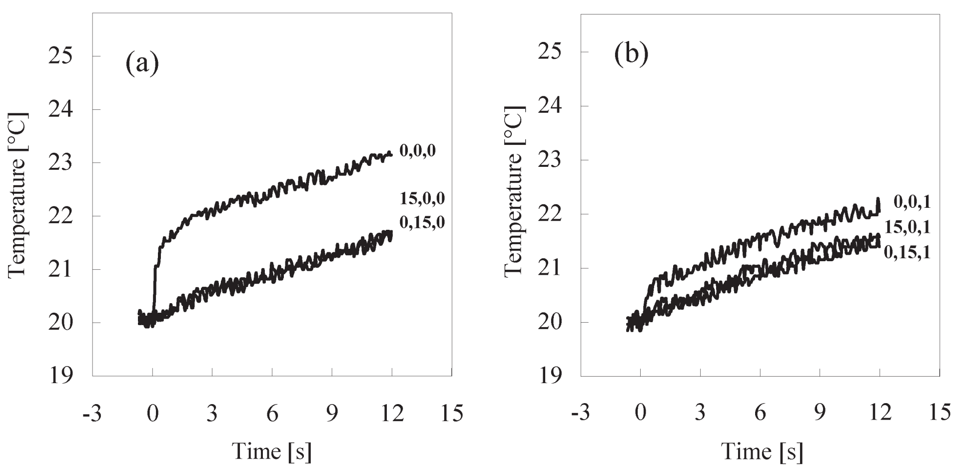

Fig. 3. Dependence of temperature on heating time for Cu-CF composite with 40 vol.% of carbon fibres: (a) exposed surface, (b) opposite surface.

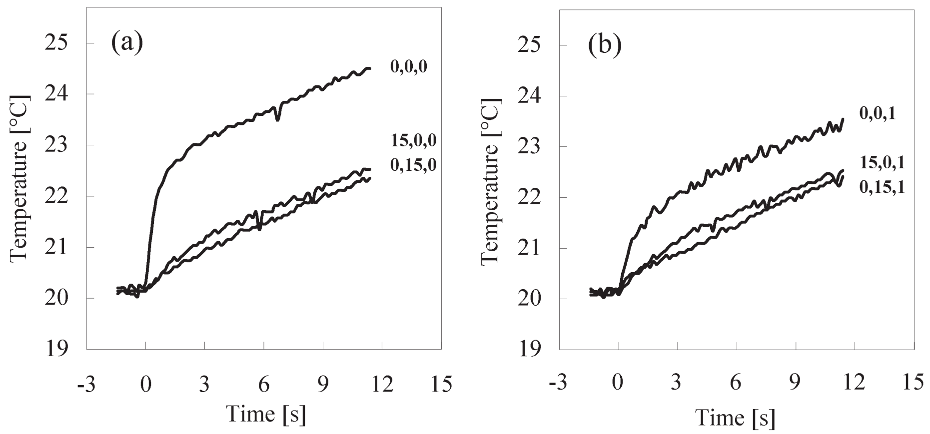

Fig. 4. Dependence of temperature on heating time for Cu-CF composite with 52 vol.% of carbon fibres: (a) exposed surface, (b) opposite surface.

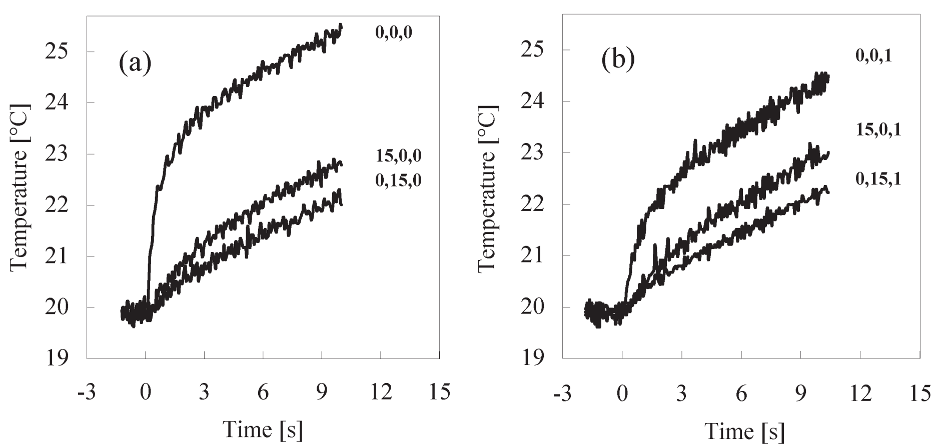

Fig. 5. Dependence of temperature on heating time for Cu-CF composite with 63 vol.% of carbon fibres: (a) exposed surface, (b) opposite surface.

of the specimen is faster for higher amount of carbon fibres in composite. This can be explained similarly as in the case of pure aluminium and copper (Figs. 2a,b). Product of the heat capacity and density is smaller for higher amount of fibres in composite (Table 1) and thus the temperature of composite on the front surface with higher amount of fibres is higher. The difference in time needed to reach the given temperature in the points [0, 0, 0] and [0, 0, 1] is due to different thermal diffusivities of composites with unequal volume fraction of CF – the higher fraction of fibres the shorter time.

The time dependencies of temperature measured at the distance of 15 mm from the centre of composite in x- and y-directions are approximately the same as those measured on the back side (co-ordinates [15, 0, 0] and [15, 0, 1]) and depend on the amount of fibres. Shift of temperature measured at [15, 0, 0] from that of [0, 15, 0] increases with the amount of fibres from approximately zero for 40 vol.% CF to more than 0.5 ℃ (after 12 s of heating) for 63 vol.% fibres. The same results are valid for back side of the sample ([15, 0, 1] and [0, 15, 1]).

Rate of temperature increase in x-direction comparing with that in y-direction is higher due to lower thermal conductivity of carbon fibre in transverse direction (0.8 W/mK – this is the thermal conductivity across the carbon fibre, e.g. in

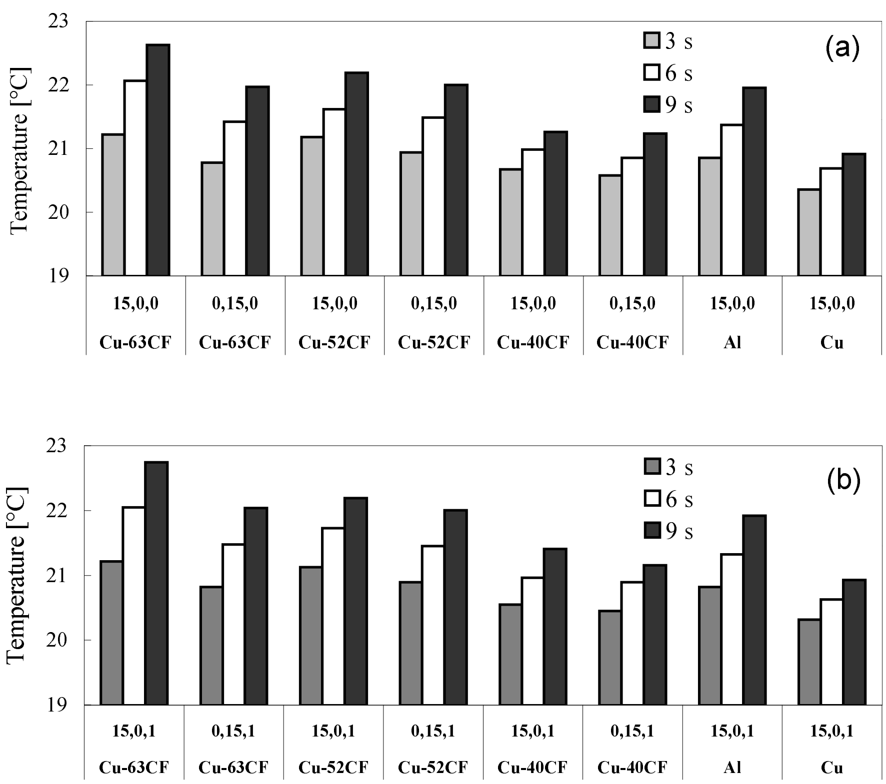

Fig. 6. Temperature in defined points of all studied samples for 3, 6, and 9 s of heating time: (a) exposed surface, (b) opposite surface.

y- and z-directions of composite) [4]. This fact starts to manifest for composites with higher amount (52 vol.%) of CF. The higher the volume amount of carbon fibres the bigger is the shift between temperature curves measured in x-direction at $[15, 0, 0]$ and in y-direction at $[0, 15, 0]$. This is also due to lower thermal diffusivity in y-direction than in x-direction. The same is valid for back side of the specimen ($[15, 0, 1]$ and $[0, 15, 1]$ co-ordinates). The facts listed above are more expressive for longer distances from the centre of the specimen.

Initial changes of temperature (until 9 s) for studied specimens are in Figs. 6a,b. The differences in temperature in various locations, as they were discussed earlier, start to be seen for the highest amount of fibres in composite (63 vol.%).

The thickness of the sample is an important parameter. In thin sheets the temperature on the exposed surface is practically the same compared to opposite face. From the temperature increase after thermal exposure of thin sheet one can deduce that the composite with 40 vol.% of CF is better than aluminium. Removing of heat from the surfaces holds the important role in these experiments. Our future work will be focused on the explanation of these effects by numerical methods.

4. Conclusion

Measurement of heat transfer across (z-axis) the unidirectional fibre reinforced composite shows that notable amount of heat is shed in (x-y) plane. Unidirectionality of fibres arrangement and their volume fraction play an important role in heat propagation in composites. In order to be successful in removing excessive heat, it is necessary to prepare composites with homogeneous distribution of heat in x-y plane and to increase their transverse thermal conductivity. First requirement results from the necessity to come close with coefficient of thermal expansion of composite to the holder of electronic elements. The second one increases the quality of heat sink.

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