INVESTIGATION OF THERMAL DIFFUSIVITY OF COMPOSITE MATERIAL BY 'MIRAGE EFFECT'

X. R. Zhang, C. M. Gan, and J. Y. Zhou
The Lab. of Modern Acoustics and Institute of Acoustics,
Nanjing University, Nanjing 210093, China

F. C. Wang and M. F. Ying
Department of material, Hefei Industry University
Hefei, Anhui 320009, China

INTRODUCTION

Thermal diffusivity is one of the important physical properties of composite materials, no matter it is used as structural or functional elements. The determination of thermal diffusivity of composite is important. Copper-Carbon and Silver-Carbon fiber composites (here after Cu-Cf and Ag-Cf) possess the properties of both of Cu and Carbon fiber. The properties of the composite are adjusted within a certain range by changing the volume and/or arrangement of carbon fiber. Thus to study the thermal diffusivity of Cu-Cf as a function of the volume fraction and the arrangement of Carbon fiber is significant for seeking the condition of that the composite with light weight, high strength, appropriate thermal diffusivity and electrical conductivity, for example, it is possible to make Cu-Cf near to metal element Mo. 'Mirage effect' method used first by Kuo et. al.[1] is a useful tool for determination thermal diffusivity of materials. The advantages of it are local, contactless and sensitive. So far, the value of thermal diffusivity for isotropic materials from the lowest value 5 10E-5 cm^2/s of polymer to the highest 18.5 cm^2/s of diamond respectively were obtained by Kuo et. al.[2,3]. The anisotropic thermal diffusivity was measured by Zhang et. al.[4]. However few of the reports are related to composites [5].

Here, the thermal diffusivities of Cu-Cf and Ag-Cf determined by 'Mirage effect' used in skimming way, the relations between the thermal diffusivity of Cu-Cf composite and fraction of carbon component as well as the arrangement of fibers within it are presented. The comparison between experimental results and theoretical modes are given.

PRINCIPLE AND EXPERIMENTAL SYSTEM

The principle of 'Mirage effect' (i.e. optical beam deflection-OBD) shows in Fig. 1. is well known[1,6,7], the deflection signals are given by formulas as

$$\Phi = -\int_l dn/(ndT)\, \nabla T_g \times dl\,; \qquad \Phi = kA\varphi_n + i\,B\varphi_t \qquad (1)$$

$$Tg = \exp(-z/g)(Ts) \quad (2)$$

where n is the refractive index of gas, k and i are the unit vector of coordination along Z and X axes respectively, T_S and Tg are the temperatures of sample and gas respectively, and they can be obtained from thermal conduction equation and boundary condition. Thermal diffusivity D of material can be got from the equation as following,

$$D = (\pi\gamma)^{-1}\{(X_1 - X_2)/[(1/\sqrt{f_2}) - (1/\sqrt{f_1})]\}^2 \quad (3)$$

where X_1 or X_2 is the distance of two zero crossing points as frequency being f_1 or f_2, γ is the parameter depending on material[1,4,6]. The experimental system, established by Nanjing Univ., is shown in Fig. 2. A CO_2 laser is used as a pump beam, a He-Ne laser is used as a probe beam. The probe beam deflection takes place, while the pump beam impinges a surface of sample. The deflection signal received by a position sensor is fed into a lock-in amplifier and is transferred to computer for data processing.

EXPERIMENTAL RESULTS

A Ag-Cf with 3 percent Carbon fiber and two series Cu-Cf wafers with diameter and thickness of 20 mm and 1.4 mm, fabricated by Hefei Industry Univ., are used as the samples. One series of Cu-Cf wafers is recombined with Cu matrix and different fractions of C-fibers components from 5 to 30 percent respectively. The fibers are cut into short fibers with length of 0.5 mm and randomly distributed in the Cu matrix of composites. The other series wafers are consisted of Cu matrix and fibers arranged in different way, such as random, plain weave or orthogonal and spiral types respectively. The properties of Cu, C-fiber and Cu-Cf are shown in table 1 to table 2. In table 2. the parameters with subscripts t

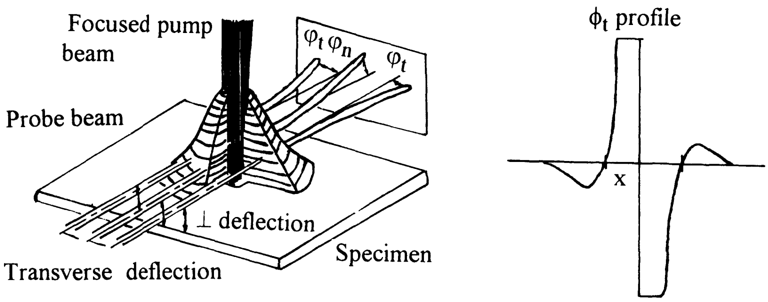

Figure 1. Schematic drawing of 'Mirage effect' (OBD method).

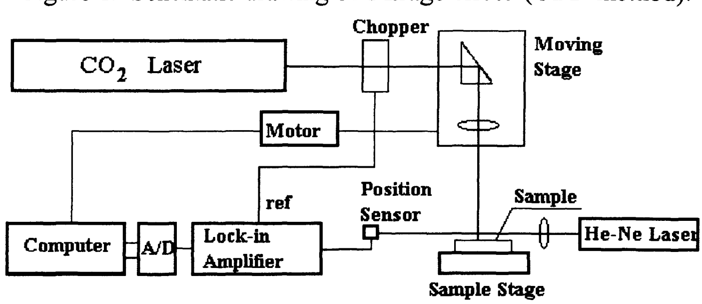

Figure 2. Experimental arrangement of 'Mirage effect' (OBD).

Table 1. Properties of Cu, Carbon fiber and Cu-Cf composites(CMP) materials.

properties materials	fraction v %	density ρ_e (g/ cm^3)	conductivity K(w/cm k)	specific-heat Cp(J/g k)	diffusivity D_e(cm^2/s)
Cu	0	8.93	3.85	0.38	1.15
Carbon fibers		2.25	1.18	0.67	0.78
CMP with random short C-fiber	23	4.30	2.90	0.69	0.97
CMP with orthogonal C-fibers	40	2.60	0.46	1.01	0.17
Cmp with Spiral C-fibers	18	5.50	1.68	0.40	0.74
composite with spiral C- fibers	28	4.00	1.09	0.42	0.64

Table 2. Properties of Cu-C F composites with different fraction of component v %.

fraction of C-fiber v %	5	10	15	20	25	30	30 nature	30 rough
density measured ρ_e (g/cm^3)	8.380	8.030	7.57	7.21	6.87	6.58	6.58	6.58
theoretical density ρ_t (g/cm^3)	8.540	8.180	7.82	7.46	7.10	6.74	6.74	6.74
porosity P %	1.900	1.900	3.20	3.40	3.30	2.40	2.40	2.40
electrical conductivity σ (Ω m)$^{-1}$	51.70	43.10	38.30	33.20	28.30	18.50		
specific heat Cp (J/kg k)	388.2	391.8	395.6	399.8	404.9	409.6		
experimental thermal difífusivity D_e (cm^2/s)	0.920	0.81	0.72	0.54	0.50	0.43	0.27	0.23
theoretical thermal diffusivity D_t (cm^2/s)	0.990	0.90	0.83	0.75	0.70	0.67		
experimental thermal conductivity K_e(w/m k)	299.6	255.4	212.5	159.0	136.9	115.9		

are the theoretical values calculated using weight method. The parameters with subscripts e are the experimental values.

Fig. 3 shows the distances of zero crossing points x versus inverse square root frequency $\sqrt{f}$ for a Ag-Cf and three Cu-Cf composites respectively. Fig. 4 shows the distances of zero crossing points x versus inverse $\sqrt{f}$ for three kinds of Cu-Cf wafers with the same fraction of fibers and with the different surface conditions respectively. The thermal diffusivities of these samples obtained by Eq. 3 are tabulated in table 2 and table 3 respectively. Fig. 5 show the experimental values of thermal diffusivities D_e of Cu-Cf versus the fractions of carbon fibers components. The experimental results indicate that:

1. The thermal diffusivity depends on the fraction of fiber components (or volume fraction)

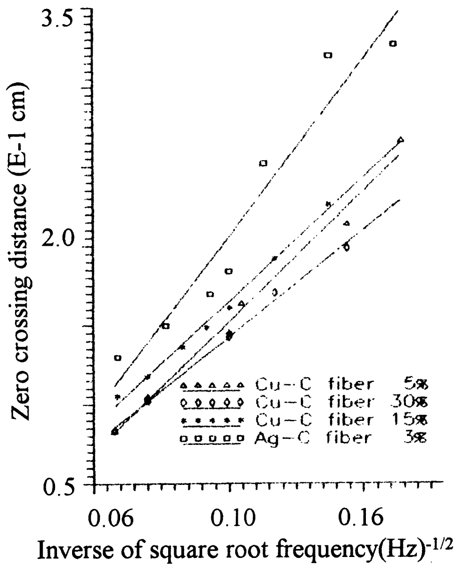

Figure 3. Zero crossing distances x versus inverse square root frequencies $(\sqrt{f})^{-1/2}$ for Ag-Cf and Cu-Cf with fractions of fibers of 3% and 5%, 15% as well as 30% respectively.

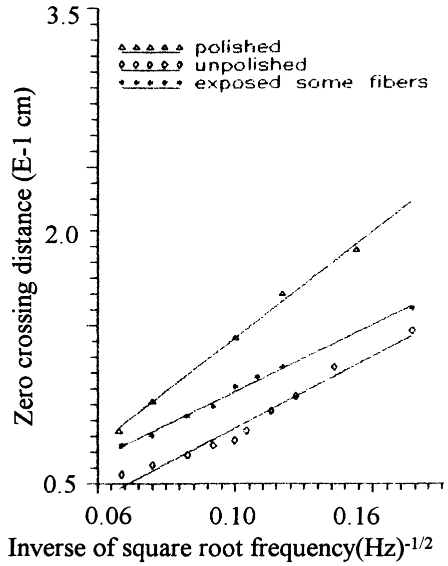

Figure 4. Zero crossing distances x versus inverse square root frequencies $(\sqrt{f})^{-1/2}$ for three Cu-Cf with 30% C-fibers and with different surface conditions, polished, unpolished and some C-fiber exposed, respectively.

and the arrangement of C-fibers. The higher the fraction, the lower the thermal diffusivity.

2. The thermal diffusivity depends on the arrangement of fibers. The thermal diffusivity for randomly distributed composite is higher than that for spiral composite and orthogonal composite. The latter is the lowest value.
3. The thermal difusivity of Ag-Cf is of 1.59 cm^2 /s which nearby to the theoretical value of 1.6 cm^2 /s evaluated by weight method.

DISCUSSION

A number of theoretical models have been developed to estimate the effective thermal conductivities of particle and fiber reinforced composites, where combination of reinforcement with high thermal conductivity embedded in an electrically insulating material. However none is related to that with low thermal conductivity embedded in an electrically conducting material as in our case. Here which one of the these modes may be used in our case is examined by comparing the results of experiment to theory. For convenience of the comparison with the theoretical modes of effective thermal conductivity the experimental thermal conductivities K_e of Cu-Cf are calculated by equation

$$K_e = D_e \rho_e Cp \quad (4)$$

where D_e and Cp are respectively the mass density and specific heat of Cu-Cf measured. The theoretical effective thermal conductivities K_c of composites are calculated based on the various theoretical modes of effective media, such as the classical model of composite for simple granular medium [8], the modified Maxwell's model [9-10] (M-Maxwell model), the Bruggeman model [10] and the Hatte and Taya model [11-12]etc.. An expression of K_c for simple granular medium is given by

$$K_c = [3K K' \ f + (2K + K')K(1- f)] / [3Kf + (2K + K')(1-f)] \tag{5}$$

where K and K' are the thermal conductivities of matrix and granules respectively, f is the volume fraction of granules. Here the K and K' are regarded as the thermal conductivities of Cu matrix and short C-fibers respectively, f is the fraction of C-fibers. The effective thermal conductivity of composite based on the modified Maxwell's theory is expressed as

$$K_c =\{[K'(1+ 2\alpha) + 2K] + 2f [K'(1+\alpha) - K]\}/ \{[K'(1+\alpha) + K] -[K'(1-\alpha) - K]\} \tag{6}$$

where α is a non-dimensional parameter depended on thermal resistance of interface between inclusion (dispersed phase) and matrix,

$$\alpha = a_k / a , \qquad a_k = R_k K \approx L /\eta , \qquad R_k = \Delta T / Q \tag{7}$$

R_k is the specific boundary resistance defined in terms of the heart flux, Q, and the consequent temperature discontinuity, Δt, across the solid- solid interface, in contrast to Kapitza resistance that is on metal-liquid helium interfaces. L and η are the phonon mean free path and the average probability for the transmission of the phonons across the interface into the dispersion phase respectively. a_k and a are the Kapitza radius for spherical inclusions and the radius of inclusions respectively. Bruggeman theory for high volume fraction composites gives the equations of effective conductivity as

$$(1-f)^3 = [K(K_c - K')^3] / [K_c(K - K')^3] \tag{8}$$

when the $\alpha \to 0$, and

$$(1-f)^3 = [K_c / K]^3 \tag{9}$$

when the $\alpha \to \infty$. The formulations to obtain the effective thermal conductivities based on the equivalent inclusions theory developed by Hatta and Taya for two-(2D-MSFC) and three- dimension misoriented short fiber composite(3D- MSFC) are given by ,

$$K_c = K_{11} = K_{33} = K\{(1+f (K'-K) [(K'-K) (S_{11} + S_{33}) + 2K) /J] \tag{10}$$

$$J=2(K'-K)^2 (1-f)S_{11}S_{33} + K(K'-K)(2-f)(S_{11} + S_{33}) +2 K^2$$

for in-plane random short fiber (2D-MSFC), and uniform distribution,

$$K_c = K_{11} = K_{33} = K\{1- f (K-K') [(K'-K)(2S_{33} + S_{11}) + 3K] / G\} \tag{11}$$

$$G = 3(K'-K)^2 (1-f)S_{11}S_{33} + K (K'-K) R + 3K^2$$

$$R=3(S_{11} + S_{33}) - f (2S_{11} + S_{33})$$

for random short fiber 3D-MSFC, and uniform distribution, where S_{11} and S_{33} are the functions of the fiber geometry (aspect ratio β) respectively expressed by

$$S_{11} = S_{22} = [\, \beta(\beta^2 - 1)^{1/2} - \cosh^{-1}\beta \,] / [\, 2(\beta^2 - 2\,]^{3/2} \,, \quad S_{33} = 1 - 2\, S_{11} \tag{12}$$

In our case, the short C-fiber is referred to a prolate spheroid with principal axes $a_1 = a_2 << a_3$ and $\beta = a_3 / a_1$, $a_1 = 7\ \mu m$ and $a_3 = 500\ \mu m$ respectively.

The results calculated according to the (4) and (5) ~ (12) are shown in Figure 6 and Fig. 7.. Fig. 6 illustrates the comparisons between results of experiments and calculations using classical model and modified Maxwell's model. Fig. 7. present the comparisons between various calculated results. From Fig. 6. and Fig. 7., it cam be seen that all of the modes describe qualitatively that the trend of thermal conductivity decrease with the fraction of fiber increasing, but the significant deviation in quantity exists between the experiments and modes, though the magnitude of deviation is different for the different mode. The deviation for modified Maxwell is smallest than that for the other modes. It must be noted that the Bruggeman model can only be used at fraction of C-fibers larger than 30%, when $\alpha \rightarrow \infty$.

A general component weight method and counting the influence of porosity (p) are also made. The component weight for Cu-Cf is made using formula (13) and (14) as

$$K_C = \{\, [(1-f) / K] + [f / K'] \,\}^{-1} \tag{13}$$

$$D_C = K_C / [(1-f)\rho_{cu}\, C_{cu} + f\, \rho_c\, C_C\,] \tag{14}$$

The calculated results of thermal diffusivities as the functions of fractions is describes in Fig. 5. The thermal conductivities calculated are illustrated in Fig. 7 for comparison with that calculated by the other modes. It is obvious that the magnitude of deviation for weight method is far less than that for other modes.

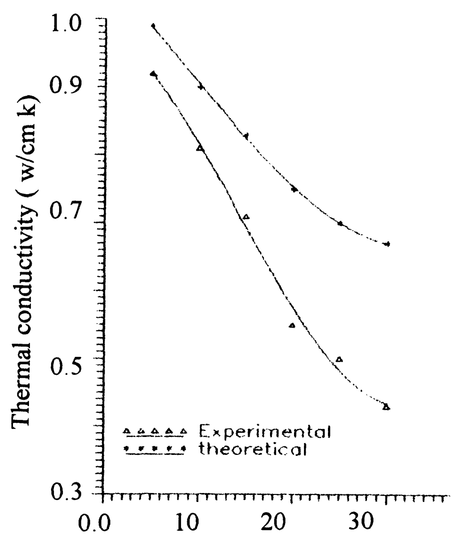

Figure 5. Thermal diffusivity of experiment and theory obtained by Eq.(14) versus fraction of fibers.

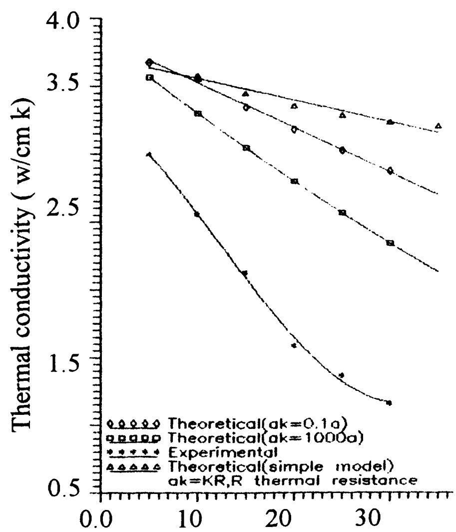

Figure 6. Thermal conductivities evaluated using M-Maxwell and classical modes and measured versus the fraction of fibers.

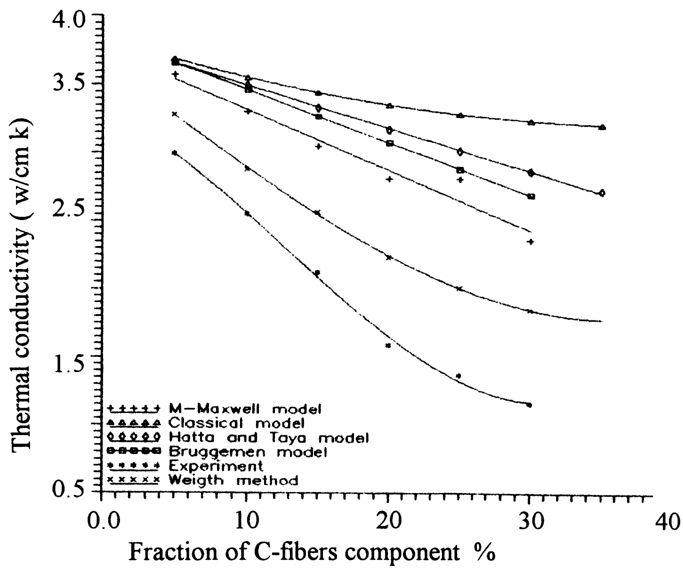

Figure 7. The comparison between various theoretical and experimental results of thermal conductivities versus the fraction of fibers, the theoretical calculation are based on the Classical model (Δ), M-Maxwell model (+) when $\alpha \to \infty$, Hatta and Taya model for 3D - MSFC (◊), Bruggemen model when $\alpha \to 0$ ( ), and weight method (×) , respectively.

The influence of porosity can be deduced from equation (5) by substituting p and k_{air} for f and k'. The ratio of $k_{air} / k \approx \infty$, because k_{air}= 0.01 w/cm k, Eq. (5) can be rewritten as

$$K_c = (1 - p) / (1 + 0.5p) \tag{15}$$

Fig. 8 explains the influence of porosity on the change of the thermal conductivity. Fig. 9 shows the comparison between the effective thermal conductivity with and without the influence of porosity on it. The results calculated by considering both of the influence from fibers and porosities are in approximate agreement with the measured results within the error of 8%. Thus it can be said that the effective thermal conductivity of Cu-Cf is contributed from multiphase influences, such as matrix, fibers, Kapitza resistance, and porosity as some air cavities in it. The weight method can be used to explain that the relation of thermal diffusivity to fraction of C-fiber for Cu-Cf material with short random arrangment fibers.

CONCLUSION

As the above mentioned, some conclusions can be obtained as following:

1. The thermal diffusivity of Cu-Cf depend on the fraction and the arrangement of fiber.
2. For a Cu-Cf sample with 25 percent fiber, its thermal diffusivity is near to that of metal Mo. we can substitute this composite for Mo used as the electrodes in power semiconductor.
3. The 'Mirage effect' method is a useful tool for determination of the thermal diffusivities of metal-matrix carbon fiber composite material, and examination of surface condition.
4. The thermal conductivity of metal-matrix carbon fiber, K_c, is a function of thermal conductivities of the metal-matrix, the fiber, the Kapitza resistance, the porosity as air cavities. So a lot of research work is needed to do in the furture.

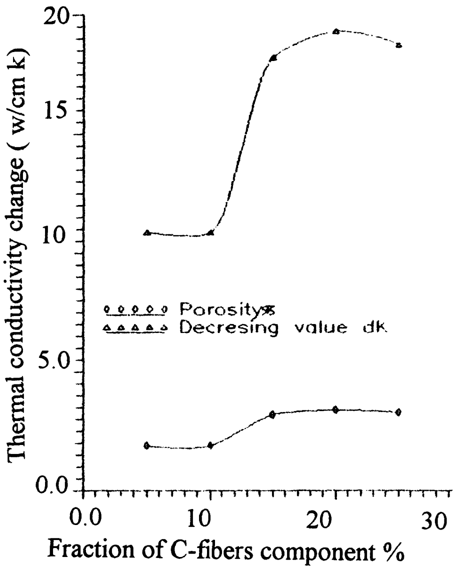

Figure 8. The Porosity and the change of thermal conductivity of Cu-Cf due to porosity versus fraction of C-fibers.

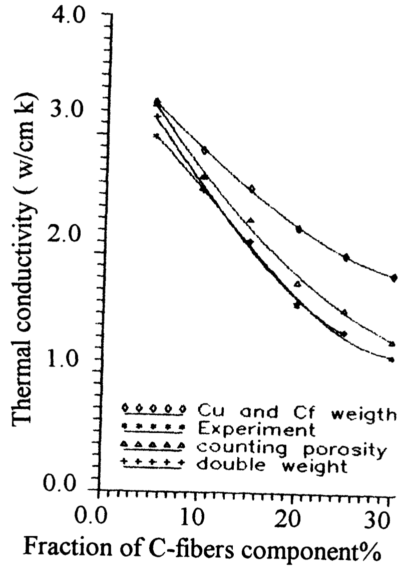

Figure 9.Thermal conductivity of Cu-Cf versus fraction of fibers, with (Δ) or without (◊) the influence of porosity.

REFERENCES

1. P. K. Kuo, M. J. Lin, C.B. Reyes, L.D. Favro, R. L. Thomas, D. S. Kim and S. Y. Zhang, Can. J. Phys. 64, (1986) 1165
2. J. Rantala, L. H. Wei and P. K. Kuo, J. Appl. phys. 73 (1993)
3. J. Ranthory et. al., and L. H. wei, P. K. Kuo, R.L. Thomas, Phys. Review B42 (1990) 1104
4. X. R. Zhang, C. M. Gan et al., Chinese Phys. Lett. 4(5) (1987) 213
5. L. J. Inglehart, F. Lepoutre and F. Charbonnier, J. Appl. Phys. 59(1) (1986) 234
6. A. Salazar, A. Sanchez-lavega and J. Fernander, J. appl. phys., 65(11) 1 (1989) 4150 J. Appl. Phys. 69(3) (1991) 1216
7. C. M. Gan and X. R. Zhang, "Springger Series in Optical Science " Vol.58 Eds. by P.Hess and J.Pelz (Springer Vellage 1988) 35
8. H. S. Carslaw and J. C. Jaeger, Conduction of Heat Solid 2rd. edt. Oxford at the Clarendon Press (1959)
9. T. C. Maxwell, A treatise on Electricity and magnetism, Vol.1 3rd. edt. Oxford Univ. Press (1904)
10. A. G.Every, Y. Tzou, D. P. H. Hasselman and R. Raj, Acta. Metall 40(1) (1992) 123
11. H.Hatta, M.Taya, J. Appl. Phys. 58(7) (1985) 2470; J. Comp. Mater. 26(5) (1992) 612
12. M. L. Dunn, M. Taya et. al., J. Appl. Phys. 73(4) (1993) 1711, J. Comp. Mater. 27(15) (1993) 1493