INFLUENCE OF SiC PARTICLES ON THERMAL PROPERTIES OF QE22 ALLOY

ALEXANDRA RUDAJEVOVÁ, PAVEL LUKÁČ

Thermal properties involving thermal diffusivity and conductivity of reinforced and unreinforced QE22 alloy were investigated in the temperature range from 20 to 300 °C. The thermal diffusivity of unreinforced QE22 alloy is practically independent of temperature while that of the particle reinforced QE22 alloys decreases with increasing temperature. In the same temperature range the addition of the SiC particles in the QE22 alloy causes a reduction in the thermal conductivity. The experimental data are discussed.

Key words: metal-matrix composites, reinforcement/matrix interface, thermal conductivity

VLIV ČÁSTIC SiC NA TEPLOTNÍ VLASTNOSTI SLITINY QE22

Teplotní a tepelná vodivost zpevněné a nezpevněné slitiny QE22 byly studovány v teplotní oblasti 20 až 300 °C. Zatímco teplotní vodivost nezpevněné QE22 slitiny je prakticky nezávislá na teplotě, teplotní vodivost zpevněné slitiny klesá s teplotou. Zpevnění slitiny QE22 částicemi SiC má za následek pokles tepelné vodivosti ve studované oblasti teplot. Jsou diskutována experimentální data.

1. Introduction

Magnesium alloys reinforced with fibres or particles have recently attracted commercial interest. Investigations of their physical and mechanical properties are important. The study of the effective thermal conductivity plays an important role in understanding the physics of metal matrix composites (MMC). The thermal conductivity of composites provides information on the thermal boundary resistance at the interface between reinforcement and matrix. In pure metals the electron contribution to the thermal conduction is dominant at all temperatures [1]. Thermal and electrical conductivity of metals are closely interconnected by the contribution of the free electrons. For materials with less metallic binding character heat transfer

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by thermal oscillation of the lattice becomes more important and for MMCs the thermal barrier resistance at the metal-ceramic interface has a significant influence on the thermal conductivity of the MMC. The heat conductivity, especially through the metal-ceramic interfaces, governs the temperature distribution in the composite and hence influences the thermal stress state of the composite. The thermal barrier resistance is determined by the mechanical or chemical adherence at the interface and by the difference in the coefficients of thermal expansion of both components of the composite.

The thermal conductivity of composites provides information on the thermal barrier resistance (called also thermal boundary resistance or interfacial thermal barrier). In the composites, where particles of one phase are dispersed in a matrix of another phase, a contribution to the thermal conductivity of the composite from interfaces can be more important than the contribution from volume of dispersed phase. The effect is stronger for smaller particles because they exhibit a greater surface to volume ratio. Hasselman and Johnson [2] first treated the influence of the thermal boundary resistance. They have proposed a model for the prediction of the effective thermal conductivity comprising the effect of interfacial resistance, which was successfully applied for several composites [3, 4]. The Hasselman-Johnson relation, applicable for spheres and fibres transverse to the heat flow direction, will be used to evaluate the experimental data of SiC particle reinforced QE22 alloy presented in this work. The main objective of this work is to estimate the effect of the particle volume fraction on the thermal conductivity of the composite. We shall try to clarify the role of the interface for the heat transfer.

2. Experimental procedure

The powder metallurgical production of the 10 and 25 vol.%SiC-QE22 MMC was carried out by hot extrusion after mixing and milling of QE22 (Mg-2.5wt.%Ag-2.0wt.%Nd rich rare earths-0.6wt.%Zr) matrix powder ($d_{50} = 39\ \mu$m) and SiC particles ($d_{50} = 9\ \mu$m). The powder/particle blends were precompacted and encapsulated. The capsules were heated up to 400 ℃ before extrusion, which was executed to a degree of deformation between $\ln(A/A_0) = 2.8$ and 3.0 [5]. (A and A_0 is the final and initial cross section, respectively). The particles became aligned parallel to the direction of extrusion showing a uniform distribution in the cross section of the extruded rods. The specimens were investigated in the experiment as extruded state.

The effective thermal conductivity (in the following called thermal conductivity) K was calculated using the relation

$$K = a\rho c, \tag{1}$$

where a is the thermal diffusivity (it represents the rate of heat diffusion per unit time), ρ is the density and c is the specific heat capacity. The measurement of the thermal diffusivity a was performed in the temperature range from 20 to 300 °C in argon atmosphere using the flash method described elsewhere [6]. The source of the light flash was a Xe-flash tube; the duration of the pulse was 1 ms. The diameter of the specimen was 16 mm and its thickness was 2.5–2.7 mm. The measurement of each experimental point of the temperature dependence of the thermal diffusivity was performed after a 10 min hold at the measurement temperature in order to start always from equilibrium state. Each curve is the average of minimum three runs. The temperature dependence of the density was calculated from the density measured at 21 °C weighing the samples in water and from respective values of volume thermal expansion measured up to 300 °C. The linear expansion was measured in argon using the Netzsch 402E dilatometer. The heat capacity of QE22 alloy was calculated using the Neumann-Kopp rule. The effective heat capacity of the composite c_{c} was calculated from the following relation

$$c_{\mathrm{c}} = (f_{\mathrm{m}} c_{\mathrm{m}} \rho_{\mathrm{m}} + f_{\mathrm{p}} c_{\mathrm{p}} \rho_{\mathrm{p}})/\rho_{\mathrm{c}}, \tag{2}$$

where f is the volume fraction and subscripts c, m and p refer to composite, matrix and particles, respectively.

3. Results and discussion

Figure 1 shows the temperature dependence of the thermal diffusivity for the QE22 alloy and two composites of QE22 matrix reinforced with SiC particles. Full curves in Fig. 1 are for rounded particles and the dotted curve is for plate-like (sharp) particles. The thermal diffusivity is the same for both types of particles. From Fig. 1 it can be seen that whereas the thermal diffusivity of the unreinforced QE22 alloy is practically independent of temperature, the thermal diffusivity of composites decreases with increasing temperature. The drop in the thermal diffusivity depends on the volume fraction of SiC particles and on temperature. From Fig. 1 it can be seen that the thermal diffusivity decreases with increasing volume fraction. The higher the temperature, the larger the decrease. Differences in the thermal diffusivity data will be elucidated in the terms of the effective thermal conductivity.

The thermal conductivity K was estimated by the method and the equation given above using the thermal diffusivity data. The temperature variations of the thermal conductivity for the QE22 alloy and composites are presented in Fig. 2. One can see that while the temperature dependence of the thermal conductivity for the 10%SiCp/QE22 composite is similar to that for the QE22 alloy, the temperature variation of the thermal conductivity for the composite with 25 vol.% of SiC particles is different from the former. It can be seen that the thermal conductivity at any temperature decreases with increasing volume fraction of SiC particles.

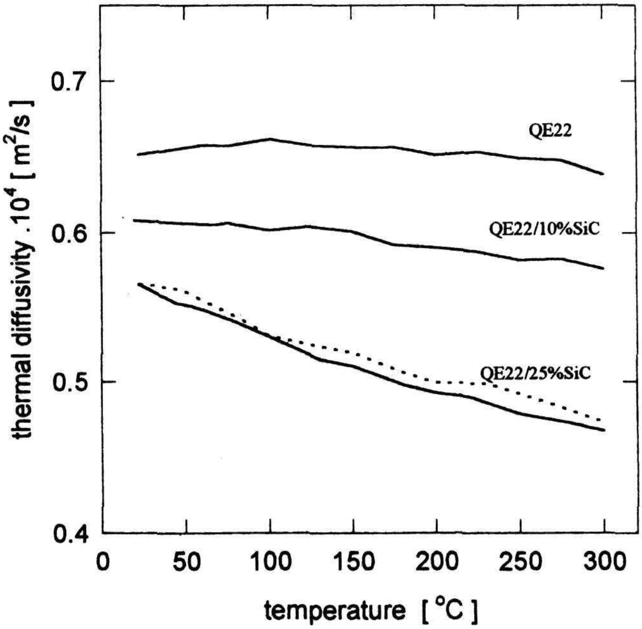

Fig. 1. Temperature dependence of the thermal diffusivity (full lines – rounded particles, dotted lines – sharp particles).

The effective thermal conductivity of composites depends on:

1. the thermal conductivity of each phase,
2. the volume fraction of the reinforcement,
3. the manner in which the phases are distributed; in particular the size, shape and orientation of each segment of each phase,
4. the nature of the contacts between the different phases.

According to [7], the thermal conductivity of SiC decreases from 90 W/m·K at room temperature to 80 W/m·K at 300 °C. The character of the interfaces between the matrix and the reinforcement can be described by thermal barrier resistance of the interface and its coefficient of thermal conductance h. The thermal boundary conductance is inverse to the thermal boundary resistance. The h-factor ($[h] = \mathrm{W/m^2 \cdot K}$) is determined by the ratio between the heat flow Q and the consequent temperature drop ΔT across the interface:

$$Q_\mathrm{i} = h \cdot \Delta T_\mathrm{i}. \tag{3}$$

For a volume fraction f of spherical particles (with radius r) in a dilute composite,

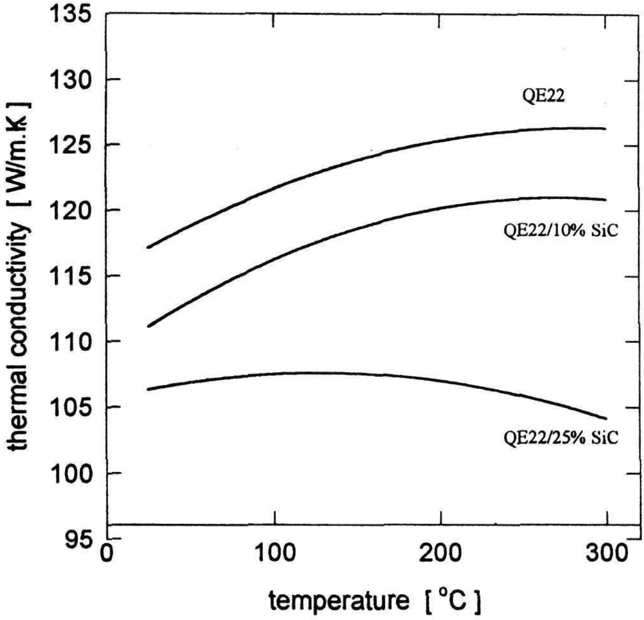

Fig. 2. Temperature dependence of the thermal conductivity.

the following analytical expression for ratio of the effective thermal conductivity of composite K_c and matrix K_m is given by Hasselman and Johnson [2]

$$\frac{K_c}{K_m} = \frac{\left[2f\left(\frac{K_p}{K_m} - \frac{K_p}{r \cdot h} - 1\right) + \frac{K_p}{K_m} - 2\frac{K_p}{r \cdot h} + 2\right]}{\left[f\left(1 - \frac{K_p}{K_m} + \frac{K_p}{r \cdot h}\right) + \frac{K_p}{K_m} + 2\frac{K_p}{r \cdot h} + 2\right]}, \tag{4}$$

where K_p represents the conductivity of particles. In the expression the ratio of the thermal conductivity of the composite and the matrix is controlled by the non-dimensional parameter $K_p/r \cdot h$ that depends on the dimension of the reinforcement and on the interfacial resistance to heat transfer. Eq. (4) can be used to estimate the interfacial thermal conductance in the composites using the experimental data presented in Fig. 2. In Fig. 3 the effective thermal conductivity data for the 25%SiCp/QE22 composite are compared with the predictions derived from Eq. (4) using the experimental conductivity values for the QE22 matrix, published conductivity values for SiC [7], and a particle diameter $d_{50} = 9$ μm. It can be seen that the experimental data are consistent with $h = 1 \times 10^8$ W$\cdot$m^{-2} K^{-1}

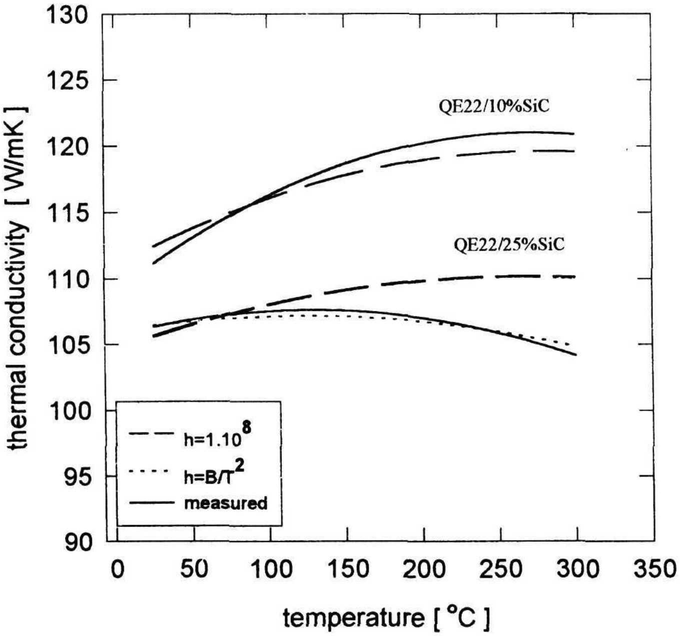

Fig. 3. Comparison of the experimental thermal conductivity with that calculated by Eq. (4).

($h \to 0$; insulating interface; $h \to \infty$; perfectly conducting interface) only for the 10%SiCp/QE22 composite in the whole temperature range investigated. The temperature dependence of the thermal conductivity of the 25%SiCp/QE22 composite cannot be described by a constant value of h; the decrease in the thermal conductivity with increasing temperature is higher than that corresponding to a constant value of h. In the case of a perfectly conducting interface the decrease of the effective thermal conductivity between matrix and composite at room temperature should be only about 10%. The experimentally determined decrease is about 22%. Hence the thermal resistance of the matrix-reinforcement interfaces reduces the effective thermal conductivity of 25%SiC/QE22 by 12%. Good agreement between measured values of the thermal conductivity and the values calculated according to Eq. (4) is obtained if it is assumed that $h = B/T^2$, where B is a constant.

The temperature dependence of h for both composites is given in Fig. 4. The value $h = 1 \times 10^8$ W/m$^2 \cdot$K characterises a good conducting interface. Gordon et al. [3] have reported h between 10^6 and 10^7 W/m$^2 \cdot$K for a 20%SiCp/Ti composite. Hasselman and Donaldson [8] have reported that the value of the interfacial thermal conductance for a 40 vol.% SiC particulate reinforced aluminium matrix composite

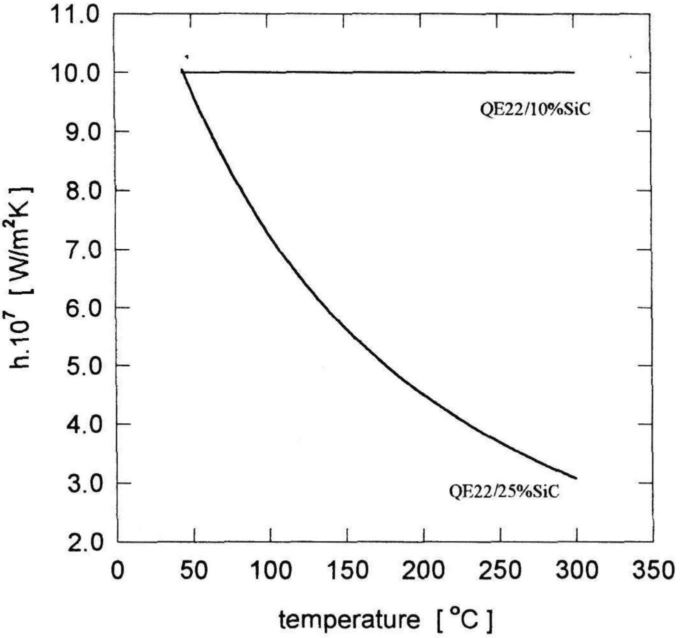

Fig. 4. Temperature dependence of the interfacial thermal conductance.

was determined to be about 1.46×10^8 W/m$^2 \cdot$K. They have also reported that the thermal conductivity of the composite (at a constant volume fraction of the particles) is a function of SiC mean particle size. The thermal conductivity decreases with decreasing size. Our results on the thermal conductivity of SiCp/QE22 composites are in qualitative agreement with the results of Hasselman and Donaldson [8]. The results can be explained by assumption that the relative contribution of the SiC particles to the total conductivity of the composites decreases with an increase in the total interfacial area. In our case, the mean particle size is constant but the volume fraction of particles increases.

The powder metallurgical production of the SiCp/QE22 MMC avoids any liquid phase reaction between the matrix and the reinforcement and leads to a more homogenous distribution of alloying elements resulting in a lower thermal barrier resistance. On the other hand, however, cooling from a high temperature of processing to room temperature and thermal treatment of composites may lead to the creation of new dislocations in the immediate vicinity of the SiC particles. These dislocations act as scatter centres for both phonons and electrons influencing the heat transmission between matrix and reinforcement. The additional thermal resistivity due to the dislocations decreases the thermal conductivity of the composite.

4. Conclusions

The addition of SiC particles decreases the thermal conductivity of the magnesium alloy QE22. The thermal conductivity of the composite is influenced by the interfacial thermal barrier that is a function of the total interfacial area and the dislocations in the vicinity of the particles due to thermal treatment.

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