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Thermal conductivity of metal matrix composites with coated inclusions: a new modelling approach for interface engineering design in thermal management

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Abstract

Despite the importance of interface engineering in technological metal matrix composites, both systematic experimental studies and modelling approaches are still lacking to predict some of their properties. This paper presents an insight into experimental results and modelling of the thermal conductivity in metal matrix composite materials with coated inclusions. Two types of composites of technological importance, Al/diamond and Mg/cobalt, have been interfacially engineered either by deposition of a 0-14.6 μm TiC layer on the diamond particles or by oxidative formation of a 0-21.4 μm Co_3O_4 layer on the cobalt particles, respectively. The experimental results of thermal conductivity can be properly accounted for by a new modelling approach that consists in a multi-step application of the GDEMS model. This modelling scheme demonstrates a predictive capacity far superior to the few current models available in the literature and allows an accurate calculation of the critical interface thickness, such that it outlines a proper interface engineering tool to design high thermally conductive composite materials.

Keywords: coating materials, composite materials, surfaces and interfaces, heat conduction, interface engineering.

1. Introduction

Predictive schemes for the physical thermal conductivity property in metal matrix composite materials are an essential tool to assess their potential use in thermal management for electronics, aeronautics or aerospace applications. Among the different modelling schemes developed for two-phase composite materials, the Maxwell mean-field (MMF) scheme and the Generalized Differential Effective Medium Scheme (GDEMS) are two approaches that take into account a finite value of the interface thermal

conductance (h) between the two solid phases [1-3]. When comparing these two models, MMF displays an inferior predictive capacity to that of GDEMS for both high inclusion volume fractions and phase contrasts (the ratio between the effective thermal conductivity of the inclusion and that of the matrix) higher than 4 [4].

The composite materials that incorporate other phases located at the interface (the so-called interfacial-engineered composite materials) have opened up new possibilities in their thermal applications, but their modelling still remains an unresolved challenge. In this regard, there are some pioneering works that have followed mainly two modelling approaches. One approach is to consider the interface as a third phase material and to then derive exact solutions based on a mean-field scheme [5,6]. This approach uses plausible yet no rigorous assumptions. For the physical limit of there being no third phases present, the modelling solutions reduce to those of the MMF scheme, with consequently clear limitations in their predictive capacities. Another approach is that adopted by Tan et al. [7], in which the different materials located at the interface can be simplified by considering a single zero-thickness interface with an equivalent h . This model is based on an electrical resistance analogy (referred to as the ER model from this point onwards), by which the overall interfacial thermal conductance h can be calculated by considering a series arrangement of thermal resistances with the following equation:

$$\frac{1}{h} = \sum \left(\frac{1}{h_i} + \frac{l_{(i-1) \rightarrow i}}{K_{(i-1) \rightarrow i}} \right) \quad (i \geq 1) \quad (1)$$

where h_i stands for the interface thermal conductance of the i_{th} interface, and $l_{(i-1) \rightarrow i}$ and $K_{(i-1) \rightarrow i}$ are the thickness and thermal conductivity of the layer from the $(i-1)_{th}$ to the i_{th} interface, respectively. h_i can be either obtained experimentally or be calculated by the acoustic mismatch model (AMM) [8] and can be later implemented into any available modelling scheme (e.g. MMF or GDEMS) to predict thermal conductivity. Tan et al. [7] used the ER model in combination with the GDEMS scheme for theoretical purposes. The ER model has been applied with relative success to various experimental systems in combination with both MMF [9,10] and GDEMS [11,12] schemes.

Nevertheless, the simplification of the ER model, which converts a certain multi-phase interface into an equivalent single zero-thickness interface, might be reasonably good for certain cases, but does present a clear drawback in those cases where the thickness of the whole interface is not negligible. Hence it represents a volume fraction that is far from being approximately zero in the overall composite material.

This work presents a new modelling approach based on a multi-step application of the GDEMS scheme and compares its predictive capacity to that of the ER-GDEMS modelling approach. Both were tested against the experimental results obtained for composites with coated inclusions. The new modelling approach accounted for the volume fraction of the coating in the composite material and proved to be accurate enough to be a good predictive tool from which important conclusions can be drawn to design interfaces in high thermally conductive composites.

2. New generalized modelling approach

The manuscript is intended to offer a generalized modelling scheme to calculate the thermal conductivity of composite materials with multi-coated inclusions. This modelling is based on the assumption that any thermal inclusion-coating couple can be modelled with the GDEMS scheme by considering that the coating acts as the surrounding matrix of the thermal inclusion. Then, for multi-coated thermal inclusions with n different concentric coatings (we assume for simplicity spherical geometry) in a matrix m , the i coating can be treated as the matrix of pseudo-inclusion materials that consist of the inner $i-1$ materials (Figure 1). Such modelling considers the subsequent coatings of the original thermal inclusions in an m -step procedure to calculate in each step the thermal conductivity of equivalent pseudo-inclusions PI_i . The final step consists in considering a composite material with a certain volume fraction (V_r) of the PI_n pseudo-inclusion surrounded by matrix m (Figure 1).

The analytical expression for the modelling approach was based on that of the GDEMS scheme, which was conveniently adapted for multi-coated inclusions:

$$\int_{K_{PI_{i-1}}}^{K_{PI_i}} \frac{dK}{K \cdot V_{PI_{i-1}} \frac{(K - K_{PI_{i-1}}^{eff})}{(K - K_{PI_{i-1}}^{eff}) S_{PI_{i-1}} - K}} = -\ln(1 - V_{PI_{i-1}}) \quad \forall i = [1, m] \quad (2)$$

where K_{PI_i} refers to the thermal conductivity of the PI_i pseudo-inclusion, K_i is the thermal conductivity of material i and $V_{PI_{i-1}}$ and $K_{PI_{i-1}}^{eff}$ are respectively the volume fraction and effective thermal conductivity of the PI_{i-1} pseudo-inclusion. In turn, $K_{PI_{i-1}}^{eff}$ and $V_{PI_{i-1}}$ can be respectively calculated by the following expressions:

$$K_{PI_{i-1}}^{eff} = \frac{K_{PI_{i-1}}}{1 + \frac{K_{PI_{i-1}}}{h_{i-1/i} \cdot (r_0 + \sum_{j=1}^{i-1} \varepsilon_j)}} \quad \forall i = [1, m] \quad (3)$$

$$V_{PI_{i-1}} = \frac{(r_0 + \sum_{j=1}^{i-1} \varepsilon_j)^3}{(r_0 + \sum_{j=1}^i \varepsilon_j)^3} \quad \forall i = [1, n] \quad ; \quad V_{PI_{i-1}} = V_r \quad \forall i = m \quad (4)$$

where $h_{i-1/i}$ is the thermal conductance of interface $i-1/i$, r_0 is the radius of the original thermal inclusion and ε_i is the thickness of coating i . $S_{PI_{i-1}}$ is the polarization factor of the pseudo-inclusion PI_{i-1} , taken as being spherical for simplicity reasons; hence $S_{PI_{i-1}} = 1/3$. Notice that for composites where $i=m$ (there being no coatings on original inclusions), the Equation (2) reduces to the well-known expression of the GDEMS model.

The interface thermal conductance h for any solid–solid interface can be accurately estimated with the acoustic mismatch model (AMM) [8]:

$$h = \frac{1}{4} \rho_{in} C_{in} v'_{in} \eta \quad (5)$$

where ρ is the density of the material, C is the specific heat, v' is the phonon velocity calculated from the longitudinal and transversal velocities, and η refers to the average probability of a phonon being transmitted across the interface. η can be in turn calculated as follows:

$$\eta = qp \approx \frac{1}{2} \left(\frac{v'_{in}}{v'_{tran}} \right)^2 \frac{4Z_{in}Z_{tran}}{(Z_{in} + Z_{tran})^2} \quad (6)$$

where q is the fraction of phonons within a critical angle of incidence, p is the transmission probability of phonons within the critical angle of incidence fraction, and Z ($Z=\rho v$) is the acoustic impedance. The subscripts “in” and “tran” in Equations (5-6) refer to the incident and transmitted sides of the phonons, respectively. v' is defined as follows:

$$v' = \left[\frac{1}{3} \left(\frac{1}{v_l'^2} + \frac{2}{v_t'^2} \right) \right]^{-1/2} \quad (7)$$

where v'_l and v'_t are the longitudinal and transverse phonon velocities, respectively. In case of data lacking, v' can be derived from its relation with the bulk modulus B :

$$v' = \left(\frac{B}{\rho} \right)^{1/2} \quad (8)$$

The incident and transmitted sides of phonons are represented by the i and the $i-1$ material, respectively.

3. Experimental procedures: materials and methods

The modelling approach was tested in two particle-containing composite systems of much technological interest. The first system consisted of Al/TiC-coated diamond composite materials, currently studied for

thermal management applications. The second system, which is important as thermally conductive magnetic materials, consisted of Mg/Co₃O₄-coated cobalt composites. The two systems differed in that the TiC coating in the first system was added to diamond inclusions to improve the poor thermally conductive aluminium-diamond interface, while the Co₃O₄ coating in the second system was formed by the oxidation of cobalt particles to protect them against reaction with magnesium during processing by liquid metal routes. Hence, an increase in Co₃O₄ coating thickness was concomitant to a reduction in the original cobalt inclusion diameter (Figure 2).

3.1 Materials

Ingots of pure aluminium (99.999%) and magnesium (99.9%) were purchased from Goodfellow Metals (Cambridge, UK). Spherical cobalt particles (99.99%), with an average diameter of about 54 µm, were also acquired from Goodfellow Metals (Cambridge, UK). Diamond particles with different average diameters in the 6-900 µm range and all with almost cubo-octahedral shape were purchased from Qiming, China. These particles were of MBD4 quality, which is one of the cheapest grades of synthetic diamond, used specially for cutting tools and abrasive applications. Figure 2 offers the electron microscopy images of the diamond and cobalt particles in their as-received conditions.

3.2 Coatings on diamond and cobalt particles

The TiC coatings on the diamond particles were performed by thermal spray deposition at the BryCoat facilities (Oldsmar, USA). The Co₃O₄ coatings on the cobalt particles were achieved by oxidation at 600°C in a quartz vertical furnace in which an air flow of 20 l/min directed from the bottom kept particles fluidized to prevent them from sticking. Before entering the furnace the air flow was dehumidified with two consecutive filters that contained silica gel and was then preheated at 500°C.

3.3 Fabrication of composites

Composites were prepared by gas pressure liquid metal infiltration into porous preforms of either the TiC-coated diamond or the Co₃O₄-coated cobalt particles. Preforms were prepared by packing particles into graphite crucibles (40 mm long and 17 mm in diameter) by a method that combined alternating strokes of a given weight and vibrations [13]. The packed preforms were gas pressure infiltrated with either liquid aluminium or magnesium at 750°C and 10 MPa (details of the pressure infiltration equipment or packing procedure can be found elsewhere [14,15]).

3.4 Characterization of composites

The coating thickness for each sample was measured with the help of image analysis software in the scanning electron microscopy (SEM, Hitachi S-3000N) micrographs on either metal-etched and fractured diamond particles (Al/TiC-diamond) or polished samples (Mg/Co₃O₄-Co). Compositional information of the coatings was obtained by EDX analysis with a probe that is coupled within the Hitachi S-3000N equipment.

The thermal conductivity of the composites was measured by means of a relative steady-state technique, in an experimental set up assembled in our laboratories following the ASTM E1225- 04 International Standard (see [16] for a detailed explanation). Samples were clamped between a water-cooled block and a reference copper sample, which was in turn connected to a hot water thermally stabilized bath at 60 °C. Losses through radiation and convection were neglected. The system was calibrated against pure aluminium (99.999 wt.%) and pure copper (99.998 wt.%), with a thermal conductivity at the measurement temperature of 237 W/m K and 398 W/m K, respectively. The temperature gradient in both the reference and sample was measured by three and two thermocouples, respectively. Thus, the linearity in the reference could also be assessed and typically fell within $\pm 1\%$. The overall uncertainty of the measured thermal conductivities was estimated to be less than $\pm 5\%$.

4. Results and Discussion

4.1 The Al/TiC-diamond and Mg/Co₃O₄-Co composites

Representative microstructures of the interfaces in both types of composite materials are provided in Figure 2. In all cases the coatings were continuous and compact, and also of homogeneous thickness. Their elemental composition, measured by quantitative EDX analysis, along with the interpretation of the present phases is gathered in Table 1. The attained particle volume fractions of reinforcement together with the measured thermal conductivity for the fabricated materials are shown in Table 2.

4.2 Comparison of the results: model vs. experiments; the ER-GDEMS model vs. the present model

The experimental results of the thermal conductivity for both the Al/TiC-diamond and Mg/Co₃O₄-Co systems (series Ai and Bi in Table 2, respectively) were confronted with the calculations performed with

the current electrical resistance analogy model (ER-GDEMS) [7] and the present modelling approach in Figure 3.

Both models showed clear differences in predictions, which are underlined below according to the analysis of the two physical limits of coating thickness (ϵ), i.e. $\epsilon \rightarrow 0$ and $\epsilon \rightarrow \infty$. For $\epsilon \rightarrow 0$ the two models coincided in calculating thermal conductivities of 595 W/mK and 100 W/mK for the Al/TiC-diamond and Mg/Co₃O₄-cobalt systems, respectively. A simple application of the GDEMS model (i.e. in Equation (2)) to the two-phase composites Al/diamond and Mg/Co (i.e. $\epsilon = 0$) gave values of 407 W/mK and 100 W/mK, respectively, in agreement with the experimental values found for the Al/diamond and Mg/cobalt systems (samples A0 and B0 in Table 2). In other words, the presence of a thin layer ($\epsilon \rightarrow 0$) of TiC at the interface of the Al/diamond composite was favourable and led to higher thermal conductivity values than when this interface is absent ($\epsilon = 0$). This was because the poor thermal conductivity of TiC (19 W/mK) was, when present as a thin coating, sufficiently compensated by the generation of two new interfaces (Al/TiC and TiC/diamond) with higher interface thermal conductance than the original Al/diamond interface (see Table 2). A different situation occurred for the Mg/Co₃O₄-Co system as the presence of poorly conductive Co₃O₄ at the interface generated two new interfaces (Mg/Co₃O₄ and Co/Co₃O₄), both with a slightly lower thermal conductance than the original Mg/Co interface (see Table 2). Both ER-GDEMS and the present model met the physical limit of $\epsilon \rightarrow 0$, which justifies the benefit of interfacial engineering in different systems of technological interest.

For $\epsilon \rightarrow \infty$, however, the two models gave different results with significantly distinct interpretations. On the one hand, the ER-GDEMS model offered values of 58 W/mK and 42 W/mK for the Al/TiC-diamond and the Mg/Co₃O₄-Co systems, respectively. In this model, when $\epsilon \rightarrow \infty$, then $h \rightarrow 0$, which meant that the interfacial thermal resistance became sufficiently large, and to such an extent that diamond inclusions did not play a significant role in thermal conduction. If this were the case, the composite material acted as a foam material in which the matrix was the only phase to substantially contribute to heat conduction. In fact the values obtained with the ER-GDEMS model coincided with the values calculated when considering metallic foams of aluminium or magnesium with pores taken as inclusions (GDEMS model with pores as inclusions – see Figure 3). Consequently, the ER-GDEMS model did not accomplish the physical limit of large coating thicknesses. On the other hand, the model presented herein predicted values of 76 W/mK (Al/TiC-diamond) and 66 W/mK (Mg/Co₃O₄-Co), which clearly agreed with both the experimental results and the calculations obtained when applying the simple GDEMS model to the two-

phase composites that contained only particles of TiC or Co_3O_4 , respectively. For the intermediate values of ϵ with a more realistic physical meaning, the model presented herein perfectly accounted for the experimental results within error. Specifically, it can be stated that the ER-GDEMS model for composites with coated inclusions was unable to account for the experimental results within error and, hence, did not constitute a proper tool to predict and design proper interfaces in composite materials.

4.3 Implications in designing of interfaces in high thermally conductive composites

This work does not only represent an incremental progress with respect to the ER-GDEMS model but also has serious implications for the design of interfaces in composite materials for thermal management applications. Since the common materials that make up engineered interfaces are normally of low thermal conductivity (carbides, refractory metals, etc [7]), their thickness must remain below certain values. The thickness critical value (ϵ_c) for a given system is an important technical and design parameter that any proper model must be able to calculate accurately. ϵ_c is defined as the maximum interfacial thickness above which the thermal conductivity of an interfacial-engineered composite falls below that of the two-phase composite material.

However, in spite that the ER-GDEMS model demonstrated in Figure 3a lacked general validity, it was able to predict a qualitative positive effect on thermal conductivity by the presence of TiC coating on the diamonds in the Al/diamond composites. In quantitative terms, the model predicted this beneficial effect for TiC coatings below 270 nm (which agrees with the predicted value found in [7] for the same system). Nevertheless, the experimental results provided in Figure 3a show this effect up to approximately 1.2 microns, which perfectly agrees with the predictions made by the present generalized approach (compare the crossing points of the calculated lines that correspond to Al/diamond and Al/TiC-diamond in Figure 3a). Moreover, while the present model was applied, ϵ_c was found not to be constant for a given system (which clearly contradicts the main conclusions in [7]), but depended instead on the particle size of inclusions according to Figure 4a. The values obtained with the present model were superior to those from the ER-GDEMS model, and the difference between both models increased for higher sized inclusions. In practical terms, a higher ϵ_c implies greater flexibility in interfaces design.

Figure 4b shows a contour plot of thermal conductivity in the Al/TiC-diamond system, calculated according to TiC thickness and diamond particle size for the ranges of interest in thermal management.

The plot also displays a broken line, which indicates the thickness critical values (ϵ_c) of TiC in the Al/TiC-diamond system. This line is virtually crossed vertically by the type Ai samples, previously analysed in Figure 3a, with varying TiC coating thicknesses for a constant diamond diameter of 40 μm . To further check the modelling approach, a new series of samples was designed (AAi samples, the details of which are provided in Table 2), by this time crossing, together with sample A3, the broken line of ϵ_c horizontally. Figure 4c shows these results, in which the present modelling approach closely agrees with the experimental data.

From Figure 4b we can clearly see that for a given diamond inclusion dimension, thermal conductivity is greater for thinner TiC coatings (which could be also qualitatively predicted by the ER-GDEMS model – Equation (1)). This would, in principle, lead us to think that interfacial engineering aims to achieve interfaces that are as thin as possible. However, we must bear in mind that some of the few experimental attempts to work with very thin interfaces (in the order of 150 nm or less) have been unsuccessful to increase the thermal conductivity of composites [9,21,22]. There are physical limitations in the heat transport through thin layers due to phonon dispersion, caused specifically by loss of continuity given by crystalline imperfections, crystalline size domains and limited dimensions compared to the phonons mean free path [23]. The region in Figure 4b that insures an effective enhancement in thermal conductivity is restricted consequently to the area comprised between the broken line of ϵ_c and a horizontal line that corresponds to a thickness of about 150 nm.

The success of this proposal, which presents a modelling approach that was able to adequately predict the experimental results of thermal conductivity in composites with coated inclusions for the first time, was largely due to thorough experimental work and also to the possibility of obtaining pure and dense coatings of homogeneous thicknesses. The same calculations and considerations as those made in this study are encouraged for other composite systems of interest in thermal management, like those that contain the interfaces generated with W, Mo, Cr_7C_3 , WC, TiAl_3 , or others of potential interest, for which a deep interfacial engineering analysis is still lacking. The author believes that the present model can be used with no lack of validity for composites with multi-coated inclusions. New experiments with composites that contain multi-coated inclusions are currently being developed in our laboratories.

5. Conclusions

A new modelling approach is proposed to calculate the thermal conductivity of composite materials with multi-coated particles. Faced with new experimental results from two largely different composite systems with coated particles, we conclude that the new approach offers an adequate predictive capacity, which is superior to the current ER-GDEMS model available in the literature based on an electrical resistance analogy, which tends to underestimate the experimental values. The new modelling procedure allows to draw reliable information to design interfaces in high thermally conductive composites.

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Tables legend

Table 1. Elemental composition (in wt.%) of the coatings identified by scanning electron microscopy analysed using EDX. Each composition is the average of five independent measurements.

Table 2. The fabricated samples that correspond to the Al/TiC-diamond and Mg/Co₃O₄-Co composites. r_o refers to the inclusion radius (either diamond or cobalt particles), V_r is the volume fraction of the coated-inclusions in the composite material, ε is the coating thickness and K_{exp} and K_{calc} refer to the experimental (with 5% uncertainty) and calculated thermal conductivities, respectively. The ER-GDEMS model employs the GDEMS approach by taking the interfacial thermal conductance calculated by the electrical resistance (ER) analogy model [7]. The thermal conductance h values were calculated with the AMM (acoustic mismatch model) model [8] from the data taken from the cited references.

Figures legend

Figure 1. Schematic view of a composite material formed by matrix m and multi-coated inclusions (a), and a diagram showing the calculation procedure proposed in the present work.

Figure 2. Microstructural details of the Al/TiC-diamond (a) and the Mg/Co₃O₄-Co (b) systems. In both columns, from top to bottom: a schematic view of the coated inclusions, a micrograph of the original inclusions with no coating and a micrograph of the coatings once the composite material was obtained after infiltration – in (a) this last image after eliminating the matrix by electro-etching.

Figure 3. The experimental and calculated results of thermal conductivity for the Al/TiC-diamond (a) and Mg/Co₃O₄-cobalt (b) composites obtained with Tan's model [4] and with the present modelling scheme.

Figure 4. (a) Comparison of the critical TiC thickness calculated by the electrical analytical model and the present model according to the diamond diameter radius; (b) the thermal conductivity results calculated by the present modelling procedure for the Al/TiC-diamond composites according to the TiC coating thickness and the diamond radius – the samples fabricated and collected in Table 2 are correspondingly indicated; and (c) the thermal conductivity values for the Al/TiC-diamond composites obtained both experimentally (samples AAi and A2) and calculated by the ER-GDEMS and the present model according to the logarithm of the diamond diameter radius (in microns) – the plot also reports the results calculated by the GDEMS model for the Al/diamond system.

Table 1

	C	O	Ti	Co	Ascribed phase
Coating on diamond particles	21.0	0.7	78.3	0.0	TiC
Coating on cobalt particles	0.1	26.3	0.0	73.6	Co ₃ O ₄

Table 2

Code - material	r_o (μm)	V_r	ϵ (μm)	K_{exp} (W/mK)	K_{calc} (W/mK)		Parameters used in the calculations (K in W/mK; h in W/m ² K)
					present model	ER-GDEMS model	
A0-Al/diamond	20	0.61	0.0	398	407	407	$K_{\text{Al}}=237$ [17] $K_{\text{D}}=1450$ [15] $K_{\text{TiC}}=17$ [7,15] $h_{\text{Al/D}}=4.51 \times 10^7$ [7] $h_{\text{Al/TiC}}=2.18 \times 10^8$ [7] $h_{\text{TiC/D}}=5.87 \times 10^8$ [7]
A1-Al/TiC-diamond			0.18	530	562	452	
A2-Al/TiC-diamond			0.6	470	491	309	
A3- Al/TiC-diamond			1.2	400	402	227	
A4- Al/TiC-diamond			2.0	320	309	178	
A5- Al/TiC-diamond			3.3	200	216	141	
A6- Al/TiC-diamond			6.2	120	133	108	
A7- Al/TiC-diamond			10.3	91	101	90	
A8- Al/TiC-diamond			14.6	90	89	81	
AA1-Al/TiC-diamond	3.0	0.58	1.2	105	108	95	$K_{\text{Mg}}=156$ [17] $K_{\text{Co}}=69$ [17] $K_{\text{Co3O4}}=25$ [18] $h_{\text{Mg/Co}}=1.62 \times 10^9$ [17] $h_{\text{Mg/Co3O4}}=6.34 \times 10^8$ [17,19,20] $h_{\text{Co3O4/Co}}=1.49 \times 10^9$ [17,19]
AA2-Al/TiC-diamond	12		1.2	298	301	179	
AA3-Al/TiC-diamond	48		1.2	565	561	346	
AA4-Al/TiC-diamond	200		1.2	690	698	569	
AA5-Al/TiC-diamond	450		1.2	728	729	656	
B0-Mg/Co	27.0		0.0	98	100	100	
B1-Mg/Co ₃ O ₄ -Co	26.9		0.1	98	99	99	
B2- Mg/Co ₃ O ₄ -Co	26.1		1.7	92	88	87	
B3- Mg/Co ₃ O ₄ -Co	24.0		4.7	78	77	73	
B4- Mg/Co ₃ O ₄ -Co	21.4		7.6	72	71	65	
B5- Mg/Co ₃ O ₄ -Co	15.8		12.4	70	68	56	
B6- Mg/Co ₃ O ₄ -Co	12.5		14.6	66	67	52	
B7- Mg/Co ₃ O ₄ -Co	0.0		21.4	64	66	43

Figure 1

Figure 2

Figure 3

Figure 4

Highlights

Thermal conductivity of composite materials with multi-coated inclusions is addressed

Al/TiC-diamond and Mg/Co₃O₄-Co composites are fabricated by metal infiltration

A new modelling scheme, based on the GDMS approach, is proposed

The model allows better prediction capacity of experimental results than current models

The model allows deriving important implications in interface engineering design