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# Thermal conductivity of spark plasma sintering consolidated $SiC_p$/Al composites containing pores: Numerical study and experimental validation

Ke Chu [a,b,*], Chengchang Jia [a], Wenhuai Tian [b], Xuebing Liang [a], Hui Chen [a], Hong Guo [c]

[a] Institute of Powder Metallurgy, University of Science and Technology Beijing, Beijing 100083, China
[b] Department of Materials Physics and Chemistry, University of Science and Technology Beijing, Beijing 100083, China
[c] Beijing General Research Institute for Nonferrous Metals, Beijing 100088, China

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ABSTRACT

A simple model was introduced for describing the effect of porosity on the effective thermal conductivity of spark plasma sintered (SPS) consolidated $SiC_p$/Al composites in terms of an effective medium approximation (EMA) scheme. Numerical results of the present model were compared to an existing model of two-step Hasselman–Johnson approach and experimental data. Both models yielded very close predictions, which provided a satisfactory agreement to the experimental data, especially for the composites with porosity below 10%. At high levels of porosity the model predictions were slightly higher than the experimental values. These two models were further extended to account for the thermal conduction properties of porous composites with a multimodal size distribution or multiphase reinforced mixtures.


## 1. Introduction

Metal matrix composites (MMCs) with high reinforcement volume fractions are used for thermal management applications due to their excellent thermo-physical properties, tailorable thermal expansion and low density. Particularly, Al matrix composites containing high volume fractions of SiC particles ($SiC_p$/Al) composites are receiving the most attention as potential candidates for a variety of uses in advanced electronic packaging and are currently competing with established materials such as Cu/W or Cu/Mo in the electronic packaging industry [1].

As has been reported so far, $SiC_p$/Al composites with high $SiC_p$ volume fraction are mainly prepared by infiltration of liquid metal into the ceramic preforms [2–4]. This process often uses Al-alloys with an addition of Si and Mg to avoid formation of interfacial reaction products such as $Al_4C_3$, which has a detrimental effect on the thermo-mechanical properties of the composites. Nevertheless, the dissolved Si and Mg decrease the matrix thermal conductivity leading to a low thermal conductivity of the composites. Spark plasma sintering (SPS) applied as a new method for preparing high performance of $SiC_p$/Al composites has been presented recently [5]. The main advantage of the SPS process is that it allows fabrication of bulk materials using relatively short sintering times at low temperatures [6], which has been known to be very beneficial to the prevention of $Al_4C_3$ at the interface. However, a small portion of pores can always appear as an unavoidable phase in $SiC_p$/Al composites during the SPS process, which is linked to the non-wetting nature of SiC and aluminum, resulting in weak ceramic–metal interfaces and incomplete sintering, especially at elevated particle volume fraction. Pores can severely degrade the thermal conductivity of the composites due to scattering of the heat flow [7]. Although the effective thermal conductivity of $SiC_p$/Al composites has been extensively investigated considering different parameters such as particle shape, size, size distribution, volume fraction and interfacial thermal resistance (ITR) [8–12], very limited theoretical work [13] has been developed to quantitatively characterize the effect of porosity on the thermal conduction properties of these composites, especially in comparison with theoretical analysis and experimental results on the composites thermal conductivity associated with the porosity.

We therefore focus in this contribution on the effect of porosity on the thermal conductivity of $SiC_p$/Al composites with high volume fabrication. A reasonable model is proposed in the framework of the effective medium approximation scheme. For the purposes of assessing the predictive capacity, the present analytical model is then compared to an existing model of two-step Hasselman–Johnson approach [13] and experimental results for the thermal conductivity of SPS consolidated $SiC_p$/Al composites with various levels of porosity. Various calculational methods are used to

* Corresponding author. Address: Institute of Powder Metallurgy, University of Science and Technology Beijing, Beijing 100083, China. Tel.: +86 10 62334271; fax: +86 01 62334271.
*E-mail address:* sinygm@yahoo.com.cn (K. Chu).

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determine the relevant parameters of the composites, i.e., the thermal conductivity of constituents and the interfacial thermal conductance.

## 2. Modeling

A number of reported results [8–15] have proved that the effective medium approximation (EMA) is a simple and powerful approach in describing the essential thermal conduction properties of the composites with perfect or imperfect interface. Our idea is to develop the EMA formula to describe the thermal conductivity of particle-reinforced composites with the porosity content.

First we briefly review the EMA theory following Hasselman and Johnson [14,15]. A schematic diagram of modeling process is shown in Fig. 1. Let us consider a two-phase composite medium consisting of $n$ spherical inclusions of radius $a$ and thermal conductivity $K_p$ embedded in an effective matrix with thermal conductivity $K_m$ (Fig. 1a). We make the assumption that the $n$ inclusions are enclosed by a spherical region of radius $R$ and the interaction between the particles is negligible. The rigorous solutions for the temperature $T_p$ within the dispersed particles and the temperature $T_m$ in the surrounding matrix can be obtained, which have the following form

$$T_p = (\nabla T)\left(\frac{3}{2K_p/ah + K_p/K_m + 2}\right) r\cos\theta \tag{1a}$$

$$T_m = (\nabla T)\left[1 + V_p\left(\frac{R}{r}\right)^3\left(\frac{K_p/ah - K_p/K_m + 1}{2K_p/ah + K_p/K_m + 2}\right)\right] r\cos\theta \tag{1b}$$

where $(\nabla T)$ is the temperature gradient at a radial distance $r$ ($r \gg R$) from the centre of the spherical cluster region $R$; $\theta$ is the angle between the radius vector $\bar{r}$ and the temperature gradient; $h$ is the interfacial thermal conductance between the spherical dispersions and the matrix. $V_p$ is the particle volume fraction defined as $V_p = n(a/R)^3$.

Now we consider a multi-phase composite medium with multiple reinforcement phases ($i$) (Fig. 1b). Each of reinforcement phases contains $n$ spherical inclusions of radius, thermal conductivity, volume fraction and interfacial thermal conductance, corresponding to $a_i$, $K_{p_i}$, $V_{p_i}$, $h_i$, respectively. In such a scheme the $T_m$ depends on the cumulative effect of $N$ phases of reinforced inclusions within a region $R$, hence Eq. (1b) becomes

$$T_m = (\nabla T)\left\{1 + \left(\frac{R}{r}\right)^3 \sum_i^N \left[V_{p_i}\left(\frac{K_{p_i}/a_i h - K_{p_i}/K_m + 1}{2K_{p_i}/a_i h + K_{p_i}/K_m + 2}\right)\right]\right\} r \times \cos\theta \tag{2}$$

Now if all the inclusions are treated as an "effective homogeneous medium" of radius $R$ and thermal conductivity $K_c$, suspended in a matrix of conductivity $K_m$ (Fig. 1b), the $T_m$ at any radial location $r$ ($r \gg R$) is given as

$$T_m = (\nabla T)\left[1 + \left(\frac{R}{r}\right)^3\left(\frac{K_m - K_c}{2K_m + K_c}\right)\right] r\cos\theta \tag{3}$$

Since the two expressions, Eqs. (2) and (3), are equivalent, it follows that

$$\sum_i^N \left[V_{p_i}\left(\frac{K_{p_i}/a_i h - K_{p_i}/K_m + 1}{2K_{p_i}/a_i h + K_{p_i}/K_m + 2}\right)\right] = \frac{K_m - K_c}{2K_m + K_c} \tag{4}$$

For explicit expression of $K_c$, Eq. (4) can be rearranged as

$$K_c = K_m\left(\frac{1 + 2A}{1 - A}\right) \tag{5a}$$

with

$$A = \sum_i^N \left[V_{p_i}\left(\frac{K_{p_i}^{\text{eff}}/K_m - 1}{K_{p_i}^{\text{eff}}/K_m + 2}\right)\right] \tag{5b}$$

$$K_{p_i}^{\text{eff}} = \frac{K_{p_i}}{1 + K_{p_i}/a_i h} \tag{5c}$$

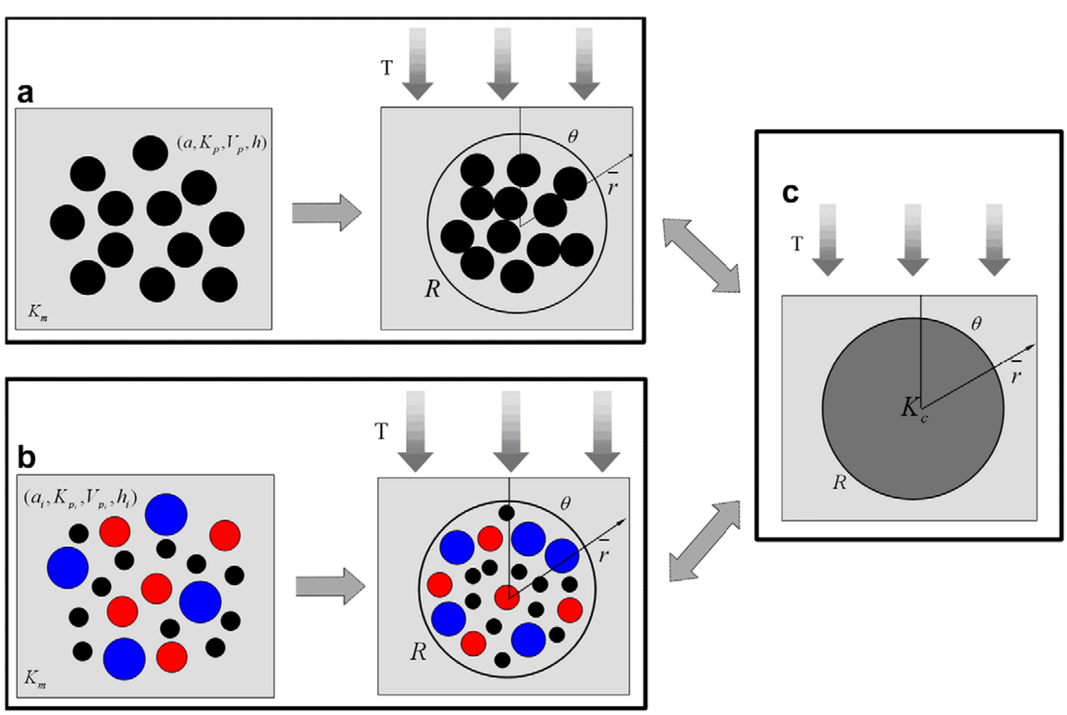


**Fig. 1.** Schematic illustration of the modeling process in terms of an effective medium approximation (EMA): (a) a two-phase composite medium consisting of unitary reinforcement phase; (b) a multi-phase composite medium consisting of multiple reinforcement phases; (c) effective homogeneous medium.