Evaluation of the Effective Thermal Properties of Metal-Matrix Composites by Considering the Filler Distribution

Juil Yoon[1*], J.H. Han[2*], E.S. Park[3], J.P. Ahn[4]

[1]*Department of Mechanical Systems Engineering, Hansung University, Seoul 136-792, Korea*

[2]*Department, Department of Nano Materials Engineering,Chungnam National University, Daejeon 305-764, Korea*

[3]*Department of Materials Science and Engineering,Seoul National University, Seoul, 151-744, Republic of Korea*

[4]*Nano Materials Research Center, Korea Institute of Science and Technology, Seoul, 130-650, Republic of Korea*

**Email; juilyoon@hansung.ac.kr*

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Abstract

For the prediction of effective thermal properties of composites, it is usually assumed that the equal-sized particles of composites are perfectly distributed in the modeling. However, the size of particles of composites may be not uniform and the alignment of particle may be not perfect, depending on their processing condition. We studied how the deviation of particle size and position affects the overall thermal properties of composites using general distribution method. It is conclude that for the controlled thermo-mechanical properties in Al-AlN composite, the particle size control is more important than the spatial position control.

1 Introduction (Times New Roman 12 pt, bold, single-line spacing left-aligned text)

Metal matrix composites (MMCs) are superior to conventional materials in terms of thermo-mechanical properties, such as stiffness, density, thermal expansion. Especially, the low coefficient of thermal expansion (CTE) of ceramics is used as reinforcement to tailor the composite to match the deformation behavior of many materials. This may indeed be useful in electronic packaging applications, where the composite/substrate junction must remain without significant distortion under temperature changes. Among the different reinforcement geometries for MMCs (fibers, whiskers, particulate), the particulate form is very attractive for many reasons such as, low prices, easier process, isotropic properties [1-5].

Aluminum matrix composites reinforced with SiC particles or AlN particles are promising candidates for high power electronics packaging applications. AlN particles reinforced aluminum matrix composites can be fabricated by pressure infiltration of liquid aluminum, powder metallurgy, partially or directly nitrided aluminum powders, and in situ reaction between Mg3N2 and Al [6-9]. We developed the AlN-Al composites by direct nitriding of aluminum via nitrogen gas injection. The process is not the scope of this study and will be reported elsewhere.

It is also important to predict thermo-mechanical properties such as effective thermal conductivity and coefficients of thermal expansion (CTE). In the 19th century, Maxwell studied the thermal conductivity of heterogeneous materials and solved the Laplace equation for randomly distributed spheres in a continuum medium. Since then, a large number of methods for evaluating thermal conductivity have been elaborated. A comprehensive review of the analytical methods was presented by [10]. For the prediction of CTE, many theatrical models are developed as well. Some models provide specific value for composite, while some offer a pair of upper and lower bounds instead [11, 12]. However, most of prediction model consider well distributed, equally spacing, and uniform filler particle size. A few studies can take into account the size distribution law of filler particles. Some experiments results show that variation of the filler size could affect the overall thermal properties of the composites [13-15]. In this article, we attempt to study the effect of variance on thermo-mechanical properties of MMC by considering the filler particle size variation, spatial distribution. It is revealed that filler particle size variation could affect on thermo-mechanical properties of MMC larger than the spatial variation.

2 The variance model considering filler particle size, spatial distribution

The thermo-mechanical properties of two-phase MMC materials depend strongly on their microstructural characteristics. In order to cover the scatter of the experimental data, several theoretical models provide the upper and lower bounds. It is the reason that the filler particle size is not uniform and filler particle is not evenly spatially distributed. In order to study the effect of the filler particle size variation and filler particle spatial variation on thermo-mechanical properties, we developed the algorism to describe the non-uniform filler particle size and spatial variation by PYTHON code. In such a way, a representative volume, in a metal matrix that contains a number n of particle of either different size and/or not evenly spatially distribution can be obtained. Using this process, we can calculate the thermo-mechanical properties as many as possible, otherwise the whole simulation process being formidable. For the particle size/spatial distribution, a normal distribution type is used, with its probability density function f(x) as following:

$$f(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \quad (1)$$

where x may be the either size of particle or spatial position of particle. μ is the mean of x and σ is the standard deviation of x. In such a way, particle size and spatial distribution can be achieved.

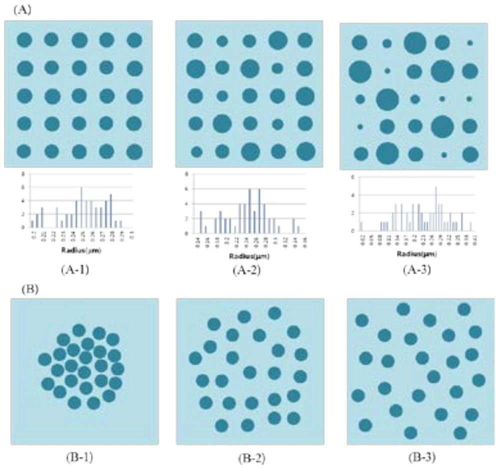

Figure 1. Schematic of simulation model for (A) particle size variation and (B) spatial variation of particle. Case A-1,2,3 denote the standard deviation (σ) of particle size are 0.02, 0.06, 0.09 respectively. Similarly, case B-1,2,3 denote the standard deviation (σ) of spatial position of particle are 10, 20, 50 respectively.

For example, Fig 1 shows the schematic of simulation model for size variation (A-1) σ =0.02 μm, (A-2) σ =0.06 μm, (A-3) σ =0.09 μm. In case A-1, the mean value μ of particle size is 1 μm and the standard deviation σ is 0.02 μm, which means the most of filler particle size are similar. In case A-3, the standard deviation σ is 0.09 μm, which means the most of filler particle size are quite dissimilar. To clarify the effect of particle size, the every filler particle locates evenly in the matrix as shown in Fig 1, so that the effect of spatial distribution can be ignored. Similarly, the schematic of simulation model for position variation (B-1) σ =10 μm, (B-2) σ =20 μm, (B-3) σ =50 μm. In case B-1, the mean value μ of particle size is also 1 μm and the standard deviation σ is 10 μm, which means the most of filler particle locate closely.

3 Results and Summary

According to the variance model, we can calculate the thermal conductivity and CTE of Al/AlN composites and also study the effect of variance of particle distribution and spatial distribution on the variance of effect of thermal conductivity and CTE of composites. In this study, we only consider the 10% volume fraction of AlN particle – Al matrix composites. □

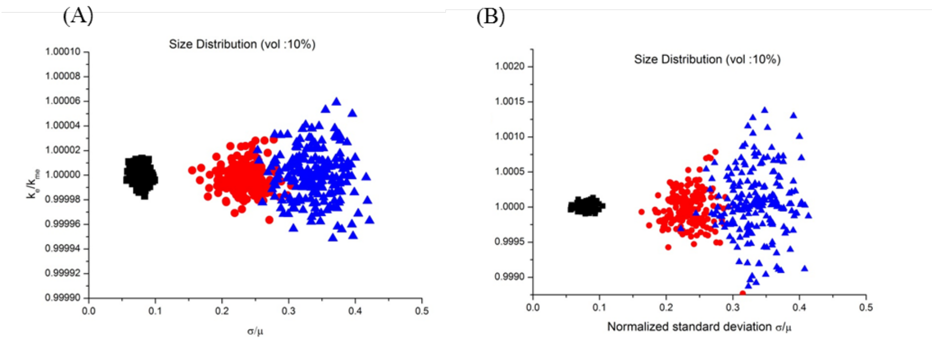

Figure 2. For the particle size distribution, **(A)** the effective thermal conductivities (k_e/k_m) and (B) the effective CTE (α_e/α_m) are plotted as a function of normalized deviation (σ/μ)

In Fig 2, the particle size effect is shown. The effective thermal conductivities (A: k_e/k_m) and effective CTE (B: α_e/α_m) are plotted as a function of normalized deviation. As the variation of particle size becomes larger, the variation of both effective thermal conductivities and effective CTE increases. In order to quantitatively compare the variation effect on thermo-mechanical properties, sensitivities of particle size on those properties are studied. The sensitivity of thermal conductivity due to particle size variation is $\sigma_{TM} \approx (\sigma_{size})^{0.9}$, while that of CTE due to particle size variation is $\sigma_{TM} \approx (\sigma_{size})^{1.7}$. It is because CTE mismatch between Al-AlN is larger than thermal conductivity mismatch. It is worthwhile to mention that the effect of particle size variation should become more significant if mismatch of particle-matrix properties, such as polymer-matrix composite is considered.

For the spatial position distribution, the effective thermal conductivities (A: k_e/k_m) and effective CTE (B: α_e/α_m) are also plotted in Fig.3 as a function of normalized deviation. the variation of both effective thermal conductivities and effective CTE are less sensitive to the particle position. It is conclude that for the controlled thermo-mechanical properties in Al-AlN composite, the particle size control is more important than the spatial position control. However, for the different mismatch of particle-matrix composite, this trend may be violated. Currently we are also considering the effect of particle orientation and shape. Some results show that the variation of shape and orientation may significantly affects the variation of effective thermal properties of composites and will be reported soon.

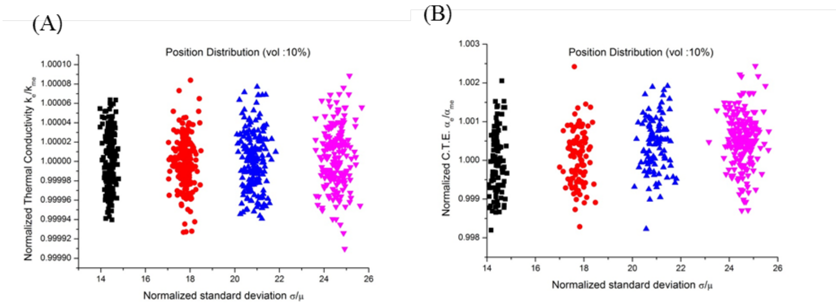

Figure 3. For the spatial position distribution, **(A)** the effective thermal conductivities (k_e/k_m) are plotted as a function of normalized deviation (σ/μ), and **(B)** the effective CTE (α_e/α_m) are plotted as a function of normalized deviation (σ/μ).

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