ESTIMATION OF EFFECTIVE THERMAL CONDUCTIVITY OF METAL MATRIX COMPOSITES BY USING IMAGE ANALYSIS

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ABSTRACT

It was aimed at the development of the software that is possible to calculate the effective thermal conductivity (ETC) of metal matrix composites from the actual microstructure image by performing conduction simulation. In this study, the statistical relationship between the three- and two-dimensional ETCs was investigated by performing the conduction simulations. The average ETC of two-dimensional cross-sections was lower than that of the corresponding three-dimensional cell, and the difference increased with increasing volume fraction. When the element size was equal to and larger than 1 μm (the particle size was larger than 10 μm), the difference between the corresponding two- and three-dimensional ETCs was small. On the other hand, when the element size was smaller than 1 μm, the difference between the corresponding two- and three-dimensional ETC was large. A correction value for converting the two-dimensional ETC to the corresponding three-dimensional ETC was suggested.

1 INTRODUCTION

The interfacial thermal resistance between the matrix and the reinforcement is thought to have a considerable effect on the effective thermal conductivity (ETC) of composites. In order to predict the effective thermal conductivity of composites, many theoretical and empirical models have been proposed. Wang et al. [1] calculated the interfacial thermal resistance by phonon diffuse mismatch model [2]. To investigate the degree of the effect of the interfacial thermal resistance, we developed a new simulation code which could calculate the effective thermal conductivity of composites with taking account of the interfacial thermal resistance. Moreover, we suggested the critical element size which could determine the optimal size of reinforcements [3]. In the present study, it was aimed at the development of the software that is possible to calculate the ETCs of metal matrix composites from the actual microstructure image by performing conduction simulation. However, the ETC calculated with the microstructure image is supposed to be not equivalent to the ETC measured with experimental method, such as laser flush analysis, because the microstructure image is two-dimensional information though the experimental conductivity is obtained from three-dimensional microstructure. As it is not well studied on the relationship between two-dimensional and three-dimensional ETC, knowledge on this relationship is necessary to evaluate ETC accurately by using the image analysis. In this study, statistical relationship between three-dimensional and two-dimensional ETC was investigated with considering the interfacial thermal resistance.

2 CALCULATION PROCEDURE

Figure 1 shows the flowchart of the calculation procedure for comparing the ETC in three- and two-dimensions. First, a three-dimensional particle distribution was created in the simulation cell, where SiC particles were uniformly distributed. The simulation cell was divided into 100 × 100 × 100 elements and aluminum heat source, each composed of 100 × 100 × 5 elements, were added to both sides. The individual element dimensions were varied from 10 × 10 × 10 μm^3 to 1 × 1 × 1 nm^3. The diameter of reinforcing particles was 10 elements and constant. By changing the size of elements, the size of the particles was varied from 100 μm to 10 nm. Figure 2 shows examples of three-dimensional simulation cell including (a) 20 vol.% and (b) 40 vol.% SiC particles, and which is cut by a cross section. The temperature distribution in the steady state was calculated by using the finite volume method (FVM), and the ETC in three- dimensions was calculated as well. Second, a two-dimensional *i*-th cross-section was extracted from the three-dimensional particle distribution. The extracted two-dimensional cross-section consisted of 100 × 100 elements, and aluminum heat source, each composed of 100 × 5 elements, were added to both sides. The ETC of the *i*-th cross-section was calculated for *i* smaller than 100. The obtained ETC (N = 100) were averaged, and the averaged value was compared with that of the three-dimensional.

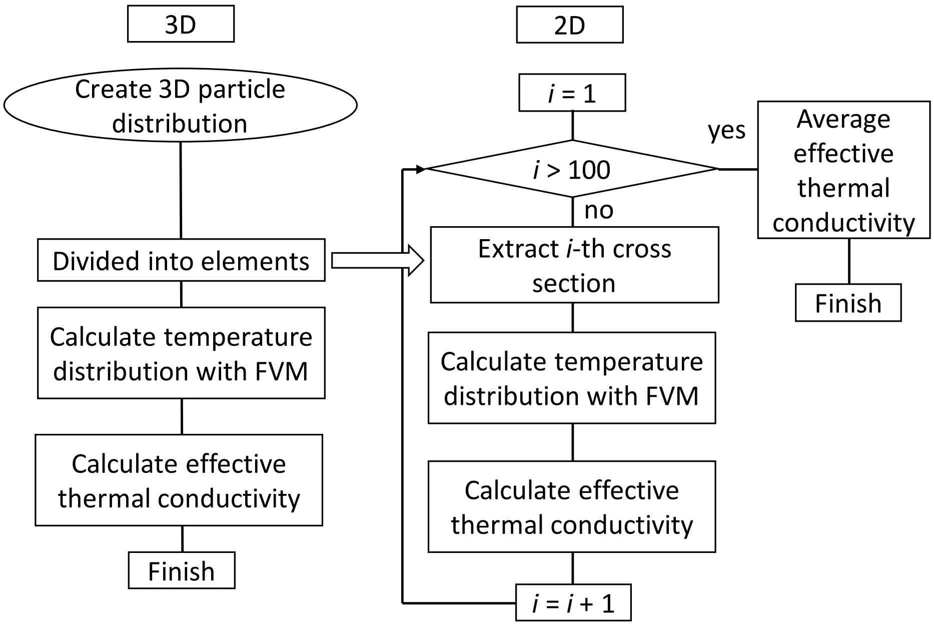

Figure 1: Flowchart of the calculation procedure for comparing the effective thermal conductivities in two and three dimensions.

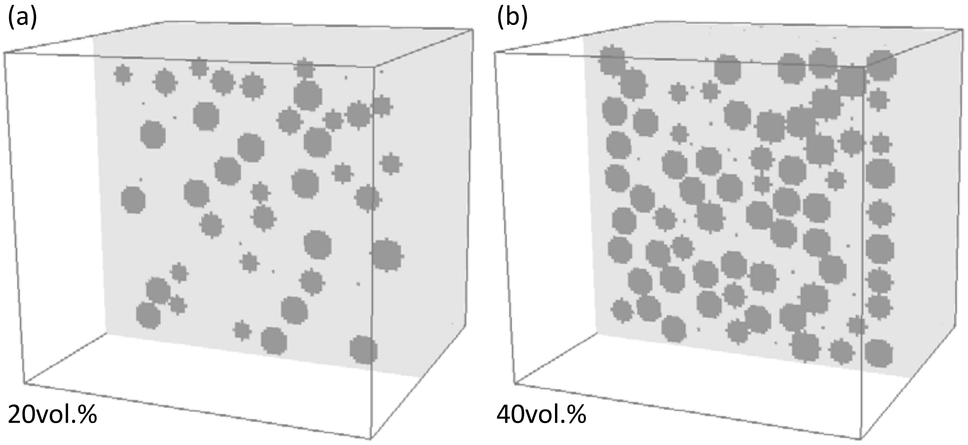

Figure 2: Three-dimensional simulation cell including (a) 20 vol.% and (b) 40 vol.% SiC particles, and which is cut by a cross section. The simulation cell was divided into 100 × 100 × 100 elements and aluminum heat source, each composed of 100 × 100 × 5 elements, were added to both sides.

Coefficient of heat transfer at the interface between Al and SiC was set to 222728062.4 W/m^2・K [1] which was calculated by phonon diffuse mismatch model [2]. The adiabatic boundary condition was applied to the surface of the simulation cell. The temperature of the left edge of the elements was set to approach temperature gradient of 4.5454×10^4 K/m and the temperature of the remaining elements was set to 300 K as initial condition. The temperature of the left and right sides of the elements was fixed and the temperature of the remaining elements was iteratively updated until average variation of temperature of each element was lower than 10^{-14}, and steady state of temperature distributions was obtained. The ETC of the composite part was evaluated from the steady state of the temperature distribution.

3 RESULTS AND DISCUSSION

Figure 3 (a) shows the ETCs of a three-dimensional cell and two-dimensional cross-sections in the Al-20vol.%SiC composite in which the element size was 10 μm. The open circles indicate the ETC of the two-dimensional cross-section that was extracted from the three-dimensional cell. The horizontal axis represents the position of the cross-section. The broken line indicates the average ETC of the two-dimensional cross-sections and individual ETCs (open circles) do not strongly deviate from the average (broken line). The ETCs of the two-dimensional cross-sections near the cell boundaries are lower than the average ETC because the density of SiC particles near the cell boundaries was low. The solid line indicates the ETC of the three-dimensional cell, and the average value for the two-dimensional cross-sections is slightly lower than the value obtained for the three-dimensional cell. Figure 3 (b) shows the relation of the ETCs of a three-dimensional cell and two-dimensional cross-sections in which the element size was 100 nm. The ETCs of the two-dimensional cross-sections near the center are lower than the values for the cross-sections closer to the cell boundaries because the density of SiC particles near the center was high and the interfacial thermal resistance affects the ETCs strongly. The difference between the two- and three-dimensional values drastically increases as compared with the difference of Figure 3 (a).

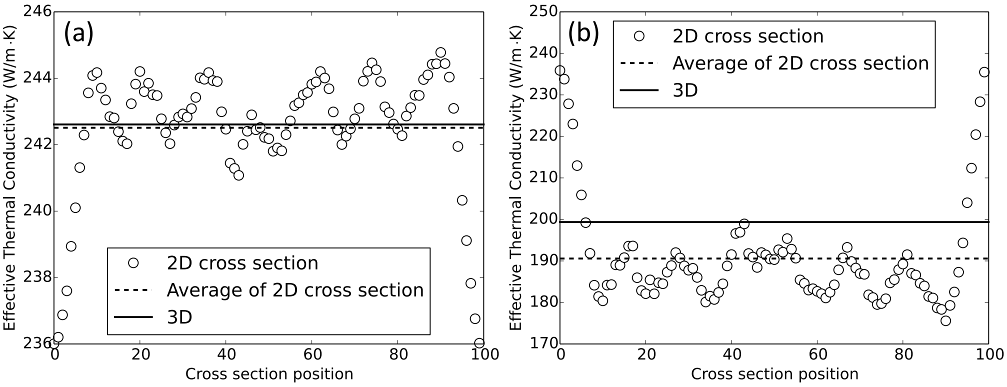

Figure 3 Effective thermal conductivities of a three-dimensional cell and two-dimensional cross-sections in the Al-20vol.%SiC composite in which (a) the element size was 10 μm and (b) the element size was 100 nm.

Series of calculations with uniform random distribution were performed by changing the element size (10 μm to 1 nm) and the volume fraction (0 % to 50 %). Figure 4 summarizes these calculations. The closed markers correspond to the ETCs of the three-dimensional cell, and the open markers indicate the ETCs averaged over the two-dimensional cross-sections. The average over the two-dimensional cross-sections is lower than the value for the three-dimensional cell. The thermal conductivities of Al and SiC were 236 and 270 W/m・K, respectively, and the ETC increases with increasing volume fraction of SiC when the element size is 10 μm and 1 μm. Meanwhile, the ETC decreases with increasing volume fraction when the element size is 100 nm, 10 nm and 1 nm. The interfacial thermal resistance affected strongly when the element size decreased. Table 1 lists the correction values for converting the two-dimensional ETC to the three-dimensional ETC. The maximal correction value is 100.06% when the element size is 10 μm. On the other hand, the maximal correction value is 180.82% when the element size is 1 nm.

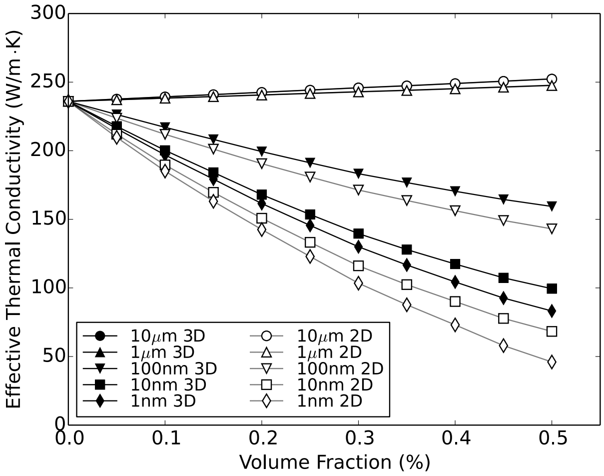

Figure 4. Effective thermal conductivities of the three-dimensional cell and the two-dimensional cross-sections. The relationship between volume fraction and the effective thermal conductivity.

Table 1. Correction values (%) for converting the two-dimensional effective thermal conductivity to the three-dimensional effective thermal conductivity.

Volume Fraction	Element Size (Particle Size)				
	10 μm (100 μm)	1 μm (10 μm)	100 nm (1 μm)	10 nm (100 nm)	1 nm (10 nm)
0.05	100.01	100.01	101.20	102.71	103.05
0.1	100.03	100.03	102.40	105.60	106.35
0.15	100.03	100.04	103.51	108.55	109.91
0.2	100.04	100.05	104.61	111.41	113.31
0.25	100.05	100.05	105.72	115.24	118.42
0.3	100.05	100.06	106.93	120.23	125.67
0.35	100.06	100.07	107.98	124.94	133.09
0.4	100.06	100.08	109.05	130.33	142.84
0.45	100.06	100.08	110.27	138.08	159.80
0.5	100.06	100.08	111.42	145.60	180.82

4 CONCLUSIONS

The statistical relationship between the three- and two-dimensional ETCs was investigated by performing the conduction simulations. The following conclusions were drawn from the current study:

(1) The average ETC of two-dimensional cross-sections was lower than that of the corresponding three-dimensional cell, and the difference increased with increasing volume fraction.

(2) When the element size was equal to and larger than 1 μm (the particle size was larger than 10 μm), the difference between the corresponding two- and three-dimensional ETCs was small. On the other hand, when the element size was smaller than 1 μm, the difference between the corresponding two- and three-dimensional ETC was large.

(3) A correction value for converting the two-dimensional ETC to the corresponding three-dimensional ETC was suggested.

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