THE EFFECTIVE THERMAL CONDUCTIVITY OF SQUARE LATTICE STRUCTURE OF HIGH FILLER LOADING COMPOSITES USING FINITE ELEMENT SIMULATION

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1. Introduction

For higher thermal conductivity, composite materials are widely used in many fields of engineering, especially in electronic products. It is because that (1) the composite materials are inherently superior to the un-reinforced matrix materials and (2) tailorability of those material properties. The effective thermal conductivity k_e of heterogeneous materials is important factors in the design of systems in which these materials are used as structural components. The development of theoretical models for thermal conductivity has long been a subject of interest. In the 19th Century, thermal conductivity of heterogeneous materials are studied by Maxwell [1] by solving the Laplace equation. After that, numerous researches for evaluating thermal property have been elaborated. For example, Benveniste [2], Hasselman and Johnson [3] improved the Maxwell model. Many semi-theoretical models were also proposed by McCullough [4]. However, these models were not applicable to high filler loading composites. For higher thermal loading composites, the simplest models, such as parallel model and series model, gives the good approximation for upper and lower bounds of the effective thermal conductivity. Agari and Uno [5], Zhou [6] made a relatively complex model to predict effective thermal conductivity. In this work, the effective thermal conductivity of square lattice structure of high filler loading composites is studied. This simple geometry model illustrates the effect of fillers on the effective thermal conductivity and forming conductive paths between adjacent fillers.

2. Square lattice structure composites

We consider composite materials that consist of square lattice fillers (shadowing areas) having higher thermal conductivity k_f and a matrix (blanking areas) having lower thermal conductivity k_m in Fig.1.

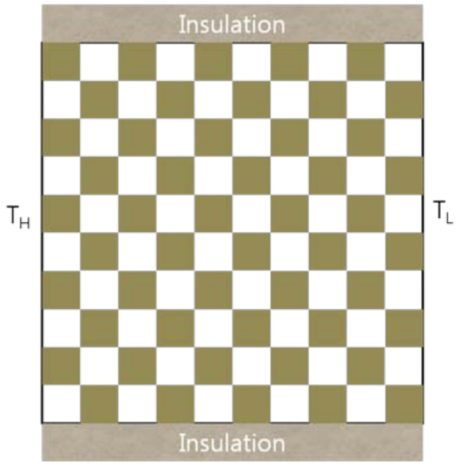

Fig.1. Schematic diagram of square lattice structure composites. The shadowing and blanking areas refer to the filler with thermal conductivity k_f and a matrix with thermal conductivity k_m respectively.

The finite element code, ABAQUS 6.9, was used to compute the heat flux of the square lattice structure composite models. As shown in Fig.1, the boundary conditions are constant high temperature for left edge and low temperature for right edge, while top and bottom edges are insulated. In the finite element model, the square fillers were tied with a matrix. Therefore, no delamination between the fillers and matrix occurs. Both fillers and a matrix are modeled as a 4-node heat transfer quadrilateral shell model

(Quad-DS4). Particular efforts were placed on meshing to guarantee sufficient mesh density and suitable element aspect ratio to achieve satisfactory computational precision.

3. Results and Discussions

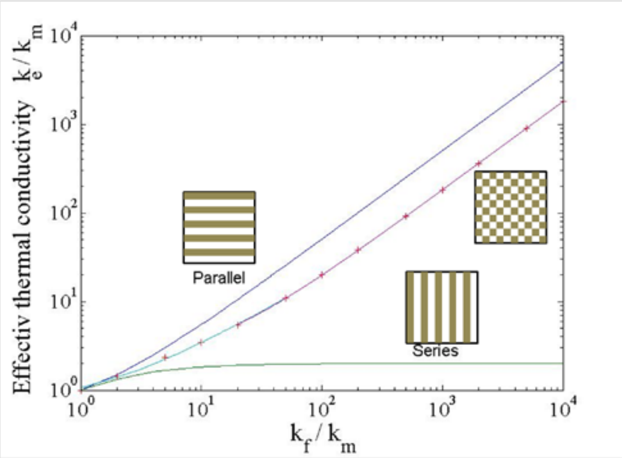

Fig.2. Effective thermal conductivity k_e/k_m of the square lattice structure composites as a function of the ratio of k_f/k_m

Figure 2 plots the effective thermal conductivity k_e/k_m of the square lattice structure composites as a function of the dimensionless thermal conductivity of fillers k_f/k_m. For comparison, thermal conductivity of parallel and series models are plotted by dotted lines. It is shown that the effective thermal conductivity of the square lattice structure composites lie between upper bounds by parallel model (1) and lower bounds by series model (2), which are shown by

- Parallel model:

$$k_e = (1 - v_f)k_m + v_f k_f \quad (1)$$

- Series model:

$$k_e = \frac{1}{k_m/(1-v_f) + k_f/v_f} \cdot \frac{k_m}{(1-v_f)} \cdot \frac{k_f}{v_f} \quad (2).$$

where, v_f is the volume fraction of fillers. In square lattice structure, the volume fraction v_f is simply ½ . For the relatively lower thermal conductivity of filler regimes (say, k_f/k_m < 2~3), the effective thermals conductivity k_e/k_m of square lattice structure composites are close to that of series model. However, as the thermal conductivity of fillers k_f/k_m becomes larger, the effective thermals conductivity k_e/k_m of square lattice structure composites follows that of parallel model. It is understood that forming conductive paths between adjacent fillers improve the heat transfer in the system, as shown Fig. 3.

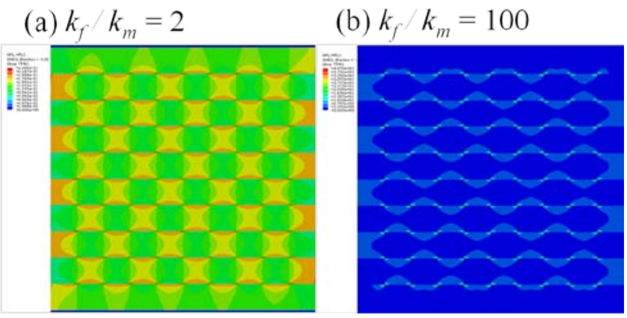

Fig.3. Contour plots of the heat flux of (a) k_f/k_m=2 (b) k_f/k_m=100.

Recently, we are trying to develop the high thermal conductivity of metal composites using (self) gas-reaction process for electronic products, such as LED heat sink. It is believed that this study can provide simple understanding and guidance for the material selection and structural optimization of the square lattice structure composites, though further theoretical investigations are needed.

References

[1] JC. Maxwell, *"A treatise on electricity and magnetism"*. 3rd ed. New York: Dover, 1954.

[2] Y. Benveniste, "Effective thermal conductivity of composites with a thermal contact resistance between the constituents: nondilute Case". *J. Appl. Phys*, Vol. 61, pp 2840–2843, 1987.

[3] DPH. Hasselman, and LE. Johnson. "Effective thermal conductivity of composites with interfacial thermal barrier resistance". *J. Compos. Mater* Vol. 21, pp 508–514, 1987

[4] RL. McCullough. "Generalized combining rules for predicting transport properties of composite materials". *Compos Sci Technol* Vol. 22, pp 3–21, 1985

[5] Y. Agari, and T. Uno. "Thermal conductivity of polymer filled with carbon materials: effect of conductive particle chains on thermal conductivity". *J. Appl. Poly. Sci* Vol. 30, pp 2225-2235, 1985

[6] H. Zhou, S. Zhang, and M. Yang. "The effect of heat-transfer passages on the effective thermal conductivity of high filler loading composite materials". *Compos. Sci. Tech.* Vol 67, pp 1035-1040, 2007