THE INFLUENCE OF SHAPE AND SPATIAL DISTRIBUTION OF METAL PARTICLES ON THE THERMAL CONDUCTIVITY OF METAL-POLYMER COMPOSITES

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ABSTRACT

In this paper, the effect of shape and spatial distribution of metal particles on the thermal conductivity of nickel-silicone composites is investigated to find out the optimum shape and spatial distribution of metal particles in polymer composites. Various finite element models with different particles shapes and arrangements are constructed to predict composite thermal conductivity.

Key word: Thermal Conductivity; Metal-Polymer Composites; Particles; Finite Element.

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1. INTRODUCTION

Polymer matrix composites filled with conductive metal particles are of particular interest in many engineering fields [1-3] due to their enhanced thermal conductivities, which are close to metal. On the other hand, the mechanical properties and manufacturing processes of such composites are typical of plastics [4]. However, introducing such a filler to the polymer matrix affects the favorable mechanical and physical properties such as high impact strength and low density. Therefore, it is of great importance to reduce the volume fraction of the conductive phase without affecting the thermal conductivity of the composite. This should be studied and predicted early in the design stage. Unfortunately, it is not always feasible to calculate the effective properties of composite material by using a specific set of equations or models. This is due to the fact that most of these equations do not take into account the peculiarities of such materials [4].
It is recognized that finite element analysis provides a direct solution to this problem [5]. In many cases, and certainly during the design stage, the finite element method has proven its reliability and accuracy, which in turn leads to a reduction in the amount of experimental work needed, and, therefore, a reduction in cost [6]. Many research works have been done on predicting the thermal properties of composites using Finite Element Modelling (FEM) [5, 7-11]. However, there are a limited number of studies that use FEM to predict the effect of the spatial distribution of conducting particles on the thermal properties of composites.

The main purpose of this study is to find out the optimum shape and spatial distribution for metal particles in polymer composites. 'Optimum configuration' here relates to the maximum heat transfer rate at the minimum volume fraction of metal particles. This is an important way of reducing the amount of metal particles without affecting the thermal transport properties of the composite.

2. MATERIAL UNDER INVESTIGATION

The metal-polymer composite investigated in this study was developed by other researchers [12] The polymer matrix is constituted of industrial silicone whereas the conductive phase is made up of nickel (Ni) particles with an average diameter of 10 µm. Two sets of samples were prepared with different volume fractions. The Ni particles in the first set being dispersed randomly in the silicone matrix, whereas the Ni particles in the second set of specimens aligned in one direction by using an external magnetic field while preparing the composite material. This technique is used to enhance thermal and electrical conductivity in one direction for the polymer matrix filled with metal particles [12-16].

3. EXPERIMENTAL MEASUREMENT

For validation purposes, this study uses the experimental work conducted earlier by Boudenne and his colleagues [12]. They used the hot guarded plate technique to measure the overall thermal conductivity of composite samples sized 15 * 15 * 3 mm³. This technique works on the principle of applying a temperature gradient on two opposite surfaces of the test specimen, placing it between heating and cooling plates while the remaining surfaces are insulated. These conditions generate a constant heat flow towards the cooled surface. Thermal conductivity is then determined as follows:

$$k = \frac{Q}{A\left(T_{\text{hot}} - T_{\text{cold}}\right)}$$

where k is the thermal conductivity of the specimen, Q is the quantity of heat flowing from the hot surface towards the cold surface, A is the surface area of the specimen, perpendicular to the heat flow, d is the distance between the hot and cold surfaces, and $T_{\text{hot}}$ and $T_{\text{cold}}$ are the hot and cold temperatures respectively.

4. FINITE ELEMENT MODELING

4.1. Composite unit cell

In order to predict the thermal conductivity of the composite, three-dimensional models for each type of Ni-Si composite (random distribution and ordered distribution) with various volume fractions of nickel, were constructed. Figure 1 (a) and (b) show two finite element models for random and ordered distributed particles, respectively. Both models with a transparent silicone matrix show the distribution of
nickel particles. The volume fraction of Ni particles in both models is 0.05. Figure (2) shows the different shapes of particles investigated in this paper, which are spherical, hexagonal, and ellipsoid. Spherical particles represent the real particles shape. Hexagonal and ellipsoid particles shapes were selected to study the effect of contact area between particles and aspect ratio of the particles on the thermal conductivity of the composite. The aspect ratio of the ellipsoid particles is arbitrarily taken to be 2.8.

![Figure 1](image1.png) Figure 1 Finite element model of (a) random (b) ordered distributed sperical particles.

![Figure 2](image2.png) Figure 2 Different particle shapes (a) spherical (b) hexagonal (c) ellipsoid.

4.2. Material properties of the constituents

The input physical and thermal properties of the silicone matrix and nickel particles are given in Table I below.

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (Kg/m$^3$)</th>
<th>Specific Heat (KJ/kg-K)</th>
<th>Thermal Conductivity (W/m-K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nickel</td>
<td>8500</td>
<td>0.445</td>
<td>90.9</td>
</tr>
<tr>
<td>Silicone</td>
<td>2320</td>
<td>1.363</td>
<td>0.25</td>
</tr>
</tbody>
</table>

4.3. Boundary conditions

The finite element calculations in this paper involve steady-state thermal analysis, yielding thermal conductivity. The steady-state analysis involves applying a temperature gradient to two opposite faces perpendicular to any spatial direction (say X), while the remaining faces are assumed to be insulated. These boundary conditions generate an unidirectional heat flow towards the cold surface. The thermal conductivity in the direction of the applied temperature gradient (k) is calculated by using Fourier’s Law, as follows:
\[ k = \frac{Q_x \Delta x}{A \Delta T} \]  

Where \( Q_x \) is the sum total of the nodal heat flux on the face with the lower temperature. \( A \) is the cross-section area of the model perpendicular to the direction of heat flow. \( \Delta x \) is the distance between the two opposite faces across which the temperature gradient is applied. \( \Delta T (T_{\text{hot}} - T_{\text{cold}}) \) is the temperature difference applied across the model. In this study, \( T_{\text{hot}} \) and \( T_{\text{cold}} \) are arbitrarily taken to be 100 and 0 °C respectively.

5. RESULTS AND DISCUSSION

The finite element (FE) results of the random and ordered distribution of spherical particles have been benchmarked against the experimental results obtained by Boudenne et al [12]. It can be clearly seen from Figure (3) that FE results follow the same trend as the experimental results with a small and acceptable margin of error. It is important to note that the values of thermal conductivity for the ordered distribution models were measured in a direction perpendicular to the orientation of the aligned particles.

![Figure 3](http://www.iaeme.com/ijmet/index.asp)

**Figure 3** Experimental and FE prediction of thermal conductivity as a function of spherical Ni particles volume fraction

![Figure 4](http://www.iaeme.com/ijmet/index.asp)

**Figure 4** FE prediction of thermal conductivity of random distribution configuration as a function of Ni particles volume fraction

Figures (4) and (5) show an increase in thermal conductivity values of the composite with respect to Ni particles volume fraction in both the random and ordered distribution configuration, respectively. It is obvious from both figures that the
ordered distribution for all particle shapes is double the thermal conductivities of the composite in a direction perpendicular to the orientation of the aligned particles.

As shown in figures (4) and (5) both spherical and hexagonal particles have nearly the same effect in both random and ordered configurations which means increasing the contact area between one particles and another will not improve the overall thermal conductivity of the composite.

![Figure 5](image)

**Figure 5** FE prediction of the thermal conductivity of ordered distribution configuration as a function of Ni particles volume fraction

As shown in figure (4), models with random distribution of ellipsoid particles have the same effect on thermal conductivity of the composite as the spherical and hexagonal particle in the range between zero and four percent nickel volume fraction. At higher nickel volume fraction (higher than 4%) random ellipsoid particle show higher thermal conductivity than spherical and hexagonal particles due to the formation of ellipsoid particles nets. The effect of ordered ellipsoid particles on thermal conductivity of the composite is more significant than models with random distribution of ellipsoid particles. Also, models with ordered ellipsoid particles have almost twice the thermal conductivity of the spherical and hexagonal particles, as shown in figure (5).

6. CONCLUSIONS

A finite element modeling approach for a nickel-silicone composite has been presented. Thermal conductivity of the composite with different particles shapes and distribution has been predicted. The predicted values of thermal conductivity were significantly influenced by the ordered distribution and aspect ratio of the particles, with the ellipsoid particles showing the highest thermal conductivity among the different particle shapes.

REFERENCES


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