学位論文要旨

Estimation of Effective Thermal Conductivity of Graphite flakes/Al Composites by Using Two-Dimensional Microstructure Images

(二次元微細組織画像を用いたグラファイトフレーク/Al複合材料の有効熱伝導率の推定)

氏 名　Zhao Yan

The rapid advancement of electronic products in the direction of high power, high frequency, miniaturization, lightweight, and integration dramatically increases the power density of electronic components, resulting in a significant increase in heat. Therefore, electronic packaging materials with high thermal conductivity, low coefficient of thermal expansion, and low density are required. Graphite flake reinforced aluminum matrix composites (GFs/Al) possess the strong workability and low-density characteristics of metallic aluminum and the high thermal conductivity and low coefficient of thermal expansion of graphite flake (GFs). GFs/Al composites are thus considered to be one of the most promising electronic packaging materials. Therefore, many experiments were conducted to study the effective thermal conductivity (ETC) of GFs/Al composites. However, the results showed that the ETC of GFs/Al composites was not as high as theoretically expected due to the effects of anisotropic thermal conductivity of GFs, interfacial thermal resistance at Al-GFs interface, chemical reactions between Al and GFs, distribution of GFs, and porosity. Especially for the anisotropic thermal conductivity of GFs, interfacial thermal resistance at the Al-GFs interface.

On the other hand, the theoretical methods commonly used to calculate ETC of GFs/Al composites include mixture rules, effective medium approximate (EMA) model, and image simulation. However, the orientation of GFs is uncontrollable and diverse in GFs/Al composites. Moreover, the anisotropic crystal structure of GFs can lead to the anisotropic thermal conductivity and the different interfacial thermal resistance at the Al-GFs interface. As a result, the orientation of GFs in GFs/Al composites dominates mainly the ETC of GFs/Al composites. Thus, Image simulation is the most suitable to calculate the ETC of GFs/Al composites considering the anisotropic thermal conductivity of GFs and interfacial thermal resistance. Image simulation includes three-dimensional (3D) and two-dimensional (2D) image simulations. 3D models of GFs/Al composites are constructed using the images from ultra-high-resolution X-ray computed tomography. The calculation is very time-consuming and expensive, resulting in low timeliness and cost-effective outcome. 2D image simulation can be performed using the optical microstructure images to calculate the ETC of GFs/Al composites. In comparison with 3D image simulation, the calculation is less expensive and timelier. Therefore, in this study, 2D image simulation was employed to calculate ETCs of GFs/Al composites considering the orientation of GFs and the interfacial thermal resistance.

Spark plasma sintering (SPS) was used to prepare GFs/Al composites in this study. SPS can provide a low temperature and high-pressure sintering environment under a vacuum. Low sintering temperature can avoid the chemical reaction between Al and GFs, and high pressure can improve the relative density of composites. Moreover, SPS can generate a plasma atmosphere to effectively destroy the oxide film on the surface of Al powders, increase new metallic contacts and necks, and reduce the porosity. GFs/Al composites with 10-40 vol. % GFs were fabricated by SPS. According to OM images, GFs were homogeneously distributed in composites, but their orientations were disordered. Moreover, with GFs contents of up to 40%, GFs tend to form a network system by

connecting GFs. The relative density was up to 99% for GFs/Al composites. XRD determined the chemical reaction between Al and GFs, and there was no Al_4C_3 was formed. A steady-state thermal conductivity measuring device measured the ETC of GFs/Al composites. The results showed that ETC increased significantly with GFs contents, but the values were great lower than the theoretical values. Additionally, the coefficients of thermal expansion of GFs/Al composites were measured. The results showed that the coefficient of thermal expansion decreased significantly with GFs contents, but the values were higher than the theoretical values.

2D image simulation was used to evaluate the effects of the orientation of GFs and interfacial thermal resistance on the ETC of GFs/Al composites. However, the orientation of GFs in 2D images may not be equivalent to the orientation of GFs in the corresponding experimental samples because a 2D microstructure image cannot provide the information in the depth direction with respect to the viewing surface. As a result, the ETC of GFs/Al composites calculated by 2D image simulations may be unreliable. Therefore, we first investigated the relationship between orientations of GFs in 3D and 2D models in the first step. The orientation of GFs was characterized by the angle between GFs basal-plane and heat flow direction. The angle was marked as θ_{2D} in the 2D cross-section and θ_{3D} in the 3D model. The studied results showed that θ_{2D} was generally larger than $\theta_{3D,}$ and the errors between θ_{2D} and θ_{3D} can cause the TC error to be as high as 840 W m^{-1} K^{-1}. The difference between θ_{2D} and the corresponding θ_{3D} did not show a regularity. Data of the θ_{2D}, $\theta_{3D,}$ and aspect ratio of GFs were on a curved surface. Finally, the curved surface function was expressed by a fitted polynomial function, using to convert θ_{2D} to θ_{3D}. Subsequently, SPS prepared four samples of GFs/Al composites, and the average angles of the GFs with respect to the heat flow direction were calculated to be 16°, 33°, 14°, and 11°, respectively in the samples. The ETCs of GFs/Al composites were evaluated using 2D image simulations and experimental methods. The orientation of GFs was considered, and the fitted polynomial function was employed in the 2D image simulations. Compared to the ETCs calculated using mixture rules and image simulations, the results showed that ETCs decreased due to the anisotropic TC of GFs by 7.2%, 9.6%, 9.9%, and 9.5% for Samples 1–4, respectively. The Comparison of the ETCs from experimental measurements and 2D-image simulations showed the effect of interfacial thermal resistance on ETC. The ETC decreased by 8.1, 9.5, 14.2, and 13.3% for Samples 1–4, respectively. Additionally, the interface heat transfer was estimated by 2D image simulation, and the value was $1.56{\sim}1.78 \times 10^7$. But the value was smaller than the values (4.8×10^7) calculated by the AMM model. The reason can be attributed to the misfits at the interface.