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Evaluation and finite element modeling for new type of thermal material annealed pyrolytic graphite (APG)

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Abstract

Annealed pyrolytic graphite (APG) has many applications in the electronics industry due to its unusually high thermal conductivity in *XY* plane. A k·Core$^{\mathrm{TM}}$ sample, manufactured by k Technology Corporation (kTC) composed of APG material with an aluminum encapsulant is evaluated and modeled by finite element analysis (FEA). The test vehicle has both 1-dimension and 2-dimension heat conduction classifications. The effect of 1-dimension versus 2-dimension is explained. Test conditions include edge cooling and thermal insulation (by plastic foam). Different combinations of test conditions (edge cooling and thermal insulation) can shift the measured temperature, but do not affect the thermal gradient. The thermal conductivity of the test sample obtained in the test is shown to be 540 W m^{-1} K^{-1}, which is 2.70 times the baseline aluminum sample (200 W m^{-1} K^{-1}). These test results were correlated back to a finite element analysis model with a positive match. The APG "benefit" is defined to be the ratio of the temperature difference between the APG sample and the baseline sample over the temperature difference between the baseline sample and ambient. The benefit of the encapsulated APG is as high as 51.67%. The study provides for a better understanding of how this new type of thermal material can be applied in electronics cooling.

Keywords: Annealed pyrolytic graphite (APG); Thermal conductivity; Finite element analysis (FEA); Edge cooling; Graphite; Diamond; Composite

1. Introduction

Pyrolytic graphite (PG) and annealed pyrolytic graphite (APG) are regarded as two of the highest thermal conductivity materials available. As a result, PG/APG has been attracting a lot of interest in different research and applications, such as carbon nanotube [1], electronics cooling [2,3], etc.

PG is manufactured through a pyrolytic reaction in a vacuum at high temperature, say 3030 °C [4] or 2150 °C [5], and APG is PG heat-treated at high temperature, say 3600 °C [6] or 3000 °C [5]. But from published data, thermal conductivity of PG/APG depends heavily on manufacturer/researcher. We can see the value varies in large range (*XY* plane), reported from 400 to 1700 W m^{-1} K^{-1} [4], 1450 to 1850 W m^{-1} K^{-1} [3], 500 to 3000 W m^{-1} K^{-1} [1], even ∼3500 W m^{-1} K^{-1} [7].

The thermal conductivity of PG/APG is heavily dependant on the temperature range. From the Holland et al. study, the peak value is ∼3500 W m^{-1} K^{-1} at ∼120 K [7]. The thermal conductivity decreases almost linearly as temperature goes up. The behavior is similar to CVD diamond. The thermal conductivity of diamond peaks (5500 W m^{-1} K^{-1}) at 160 K and decreases as temperature goes up [8]. In most electronics cooling applications, the interest is in a range from 0 to, say, 200 °C. In this range, thermal conductivity of PG/APG is even higher than CVD diamond.

For electronics cooling application, the mechanical properties of PG make it difficult to use directly. Young's modulus for PG is 20 GPa, a quarter of aluminum (80 GPa). PG tensile strength is 80 MPa [4] that is two-tenths of aluminums 400 MPa, average. To solve the problem, a kTC patented concept encapsulates APG resulting in a macrocomposite named k·Core$^{\mathrm{TM}}$. The sample evaluated in this study used an aluminum encapsulation material. kTC produces k-Core panels with a varity of encapsulating materials such as copper, Kovar$^{\mathrm{TM}}$, carbon fiber composites, copper–tungsten and aluminum–silicon. The encapsulation material is selected to provide the structural integrity and coefficient of thermal expansion control of the resulting k-Core part. k·Core parts have been qualified and are in service.

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Due to the lack of established thermal conductivity data of PG/APG and the complexity of metal encapsulation, it was considered worthwhile to investigate the actual performance of the encapsulated APG sample verses a standard aluminum plate.

The present study is focused on measuring overall thermal conductivity. Finite element analysis (FEA) was then used to confirm the testing results and for a basis for future modeling. The benefit of the new composite technology over the benchmark shows the advantage of APG technology for edge cooled applications.

2. Experimental set-up

The composite sample dimensions are $5.5'' \times 5.5'' \times 1/8''$. Inside, the APG material thickness is $0.080''$ and is sandwiched by two layers of $0.020''$ thick aluminum. The baseline sample is an aluminum plate with the same dimensions.

The test vehicle is the same set-up for both samples (Figs. 1 and 2). The composite sample and the baseline aluminum sample are mounted on identical heat sinks. Since APG has a high thermal conductivity in the *XY* plane, its cooling properties are most attractive when edge cooling is used. This forces the heat to be conducted in the *XY* plane. Both samples are clamped by the edges against the heat sinks that are cooled by fans. Loctite 5404, thermally conductive silicone, is used between the samples, clamps and heat sinks to provide a more uniform thermal conduction. The heat source is 50 W resistor with footprint of approximately $2'' \times 0.5''$ that is mounted at the opposite edge of the samples. Loctite 5404 is also used to bond the heat source on samples. Three thermocouples are attached at the bottom of the heat source cases 1, midpoint of samples 2 and near the heat sinks 3.

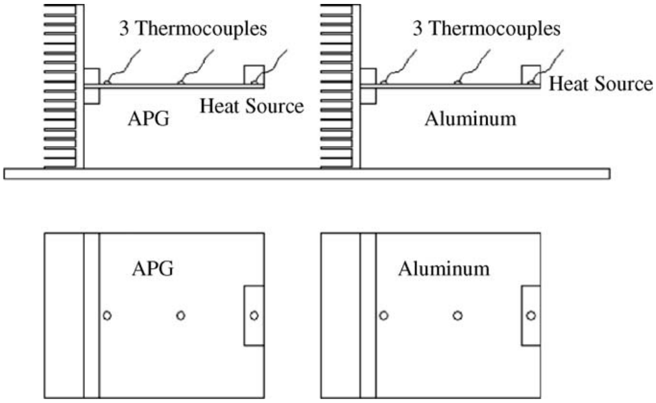

Fig. 1. Diagram of test set-up.

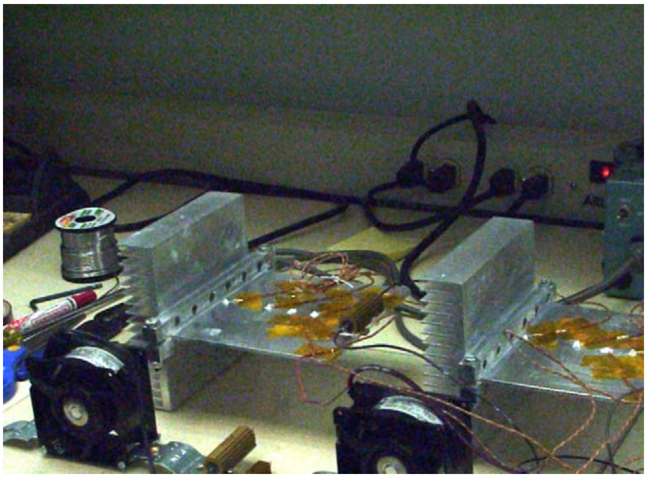

Fig. 2. Photo of test set-up.

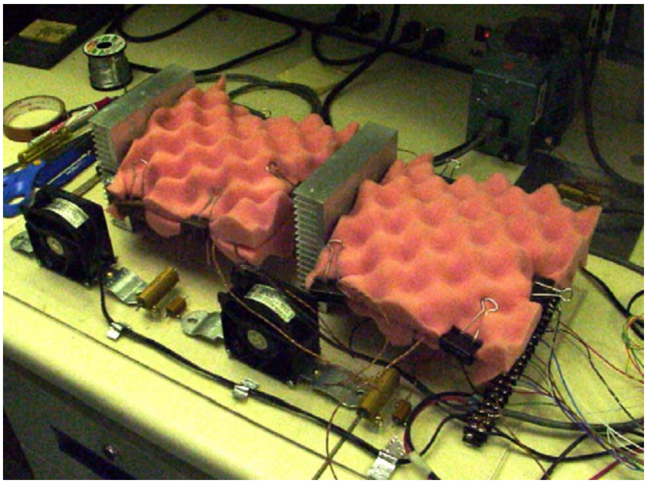

Fig. 3. Thermal insulated sample by plastic foam.

Because the dimensions of the heat source (resistor) are smaller than dimensions of the sample, the heat conduction will be in a 2-dimension direction. Plastic foam is used to wrap up the samples for thermal insulation of sample to neutralize the effect of sample surface extraneous natural convective cooling, thus allowing an isolated 2-dimension comparison between the composite and baseline materials (Fig. 3). A HP data logger is used for temperature data recording.

3. Test results

Tests were conducted for four conditions: (1) sample surface is not thermally insulated and cooling fans are on, (2) sample surface is thermally insulated and cooling fans are on, (3) sample surface is not thermally insulated and cooling fans are off and (4) sample surface is thermally insulated and cooling fans are off.

The typical test data collected for the APG composite (APG_x) and aluminum (Al_x) with the respective thermocouples are shown in Fig. 4 (testing condition 2).

For the APG composite sample, the four conditions steady state test results with each thermocouple position are shown in Fig. 5. Condition 1 gave lowest temperature overall (position 2, thermocouple 1 heat source case temp of 80 °C) and condition 4 gave highest temperature (position 2, thermocouple 1 heat source case temp of 122 °C). The difference between each of the conditions is roughly 12 °C.

Changing test conditions does not change temperature difference between thermocouples. In a plot of the curves of temperature versus position are parallel. This leads us to conclude that the thermal conductivity of the composite is relatively independent of these test conditions.

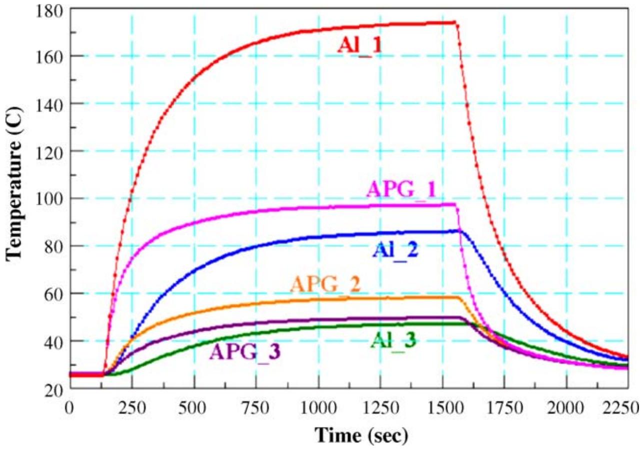

Fig. 4. Testing condition 2 data.

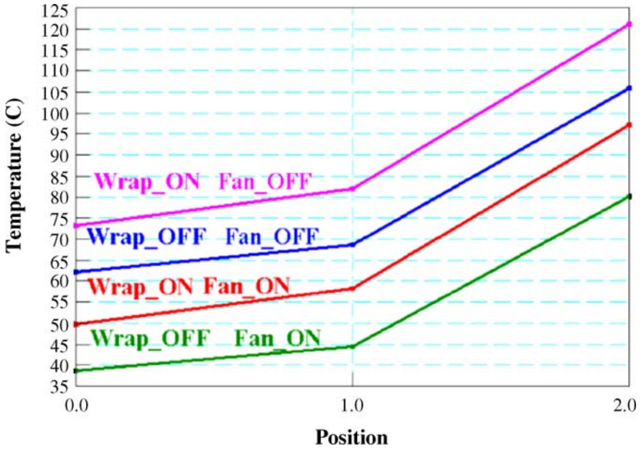

Fig. 5. Aluminum encapsulated APG sample test result.

As a result of the 2-dimension heat conduction, heat flow lines are denser as they get closer to the heat source. From thermal conductivity definition, $\Delta T \times k = (Q/A) \times \Delta X$. The heat flux ($Q/A$) in the position close to heat source is larger than (Q/A) in the position close to heat sink. ΔT between heat source and midpoint is larger than ΔT between midpoint and heat sink. So the curve for temperature versus position has two different slopes.

The strict 2-dimension thermal conduction calculation is beyond the scope of this paper. Only approximate calculations are made using baseline data. The side by side testing arrangement gave two samples with the same (Q/A) and ΔX, so $k(\mathrm{APG})/k(\mathrm{Al}) = \Delta T(\mathrm{Al})/\Delta T(\mathrm{APG})$. For example, the condition 2 data (Figs. 4 and 5) gave a $\Delta T(\mathrm{APG}) = 97 - 50\,°\mathrm{C} = 47\,°\mathrm{C}$ with a $\Delta T(\mathrm{Al}) = 174 - 47\,°\mathrm{C} = 127\,°\mathrm{C}$. The thermal conductivity of aluminum at $200\,\mathrm{W\,m^{-1}\,K^{-1}}$ is used, yielding $k(\mathrm{APG}) = 200(127/47) = 540\,\mathrm{W\,m^{-1}\,K^{-1}}$. This thermal conductivity is 2.70 times that of aluminum thermal conductivity.

4. Finite element modeling

Finite element analysis was used to confirm the test results and provide a practical basis for future models. 3-Dimension FEA models were established using Algor software as shown in Fig. 6.

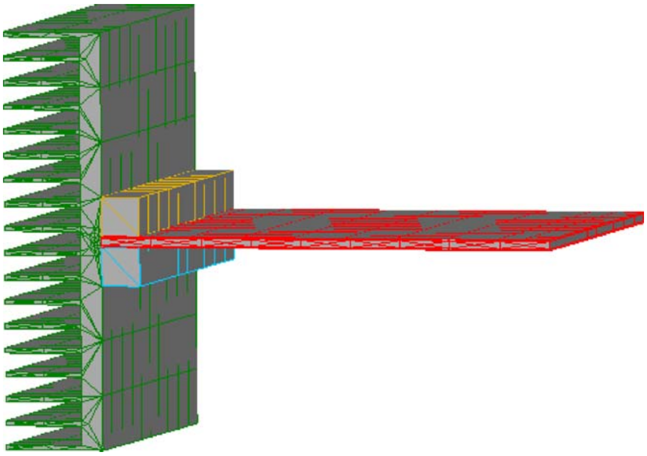

Fig. 6. FEA model for test set-up.

This model includes both the APG composite sample or the aluminum baseline plate, two clamping bars and the heat sink. The heat source is modeled by heat flux in the location of the resistor (shown at the right edge of plate). The cooling of the heat sink is modeled by surface convection. For aluminum, thermal conductivity $200\,\mathrm{W\,m^{-1}\,K^{-1}}$ is used. For the APG composite model, the orthotropic material orientation is defined by three nodes. XY plane thermal conductivity of $K_\mathrm{n} = K_\mathrm{s} = 540\,\mathrm{W\,m^{-1}\,K^{-1}}$ (derived from the test), and the Z-direction thermal conductivity of $K_\mathrm{t} = 50\,\mathrm{W\,m^{-1}\,K^{-1}}$ (a theoretical combination of APG and aluminum encapsulant) are used. From these inputs, we can derive a model simulation temperature distribution result as shown in Fig. 7.

The model results and test data of condition 2 are plotted together, shown in Fig. 8. Both the aluminum and APG composite samples models match the test results quite well. The pink line represents the aluminum test data, while the red line is the APG composite test data. The vertical error bar shows the test error. The aluminum model results are shown using blue crosses with a horizontal error bar indicating model results in the "node area". The APG composite model results are shown using green crosses with a horizontal error bar.

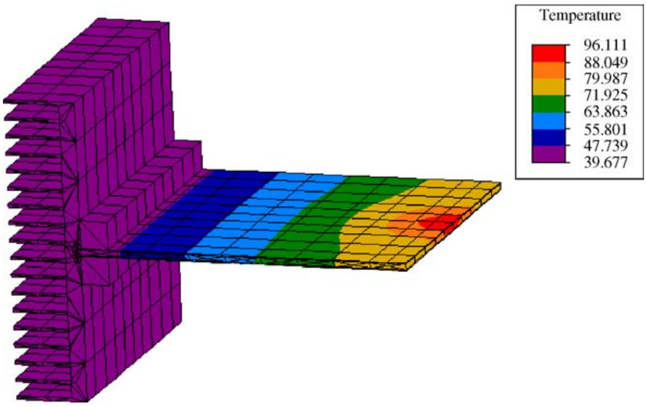

Fig. 7. Typical temperature distribution.

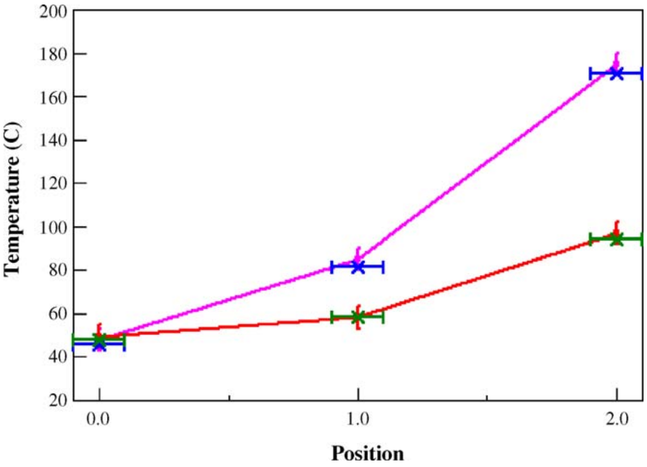

Fig. 8. Test data and modeling result of test condition 2.

5. Conclusion/summary

This paper is an application report with a first-level approximation results, and not a theoretical/academic research study. For the practical requirement of an application or engineering project, the test conducted was deemed sufficient to measure the overall thermal conductivity of a sample that is composed of APG material and aluminum encapsulant. The FEA confirmed the test result.

To express how the APG can improve the thermal performance, a benefit ratio is defined as of the heat source case temperature difference between the APG composite and the aluminum baseline over the temperature difference between the aluminum baseline and ambient. For condition 2, benefit ratio $= (T(\mathrm{Al}) - T(\mathrm{APG}))/(T(\mathrm{Al}) - T(\mathrm{ambient})) = (174 - 97)/(174 - 25) = 51.67\%$.

The selection of this study sample is based on a specific application not for theoretical study. Because of high thermal conductivity in *XY* plane, poor thermal conductivity in *Z*-direction, edge cooling is used for the plane. For the study, 3-dimension effect is not included because the assumption was made that *Z*-direction thermal losses were negligible. The sample is a material plate that the length and width are much larger than thickness.

Some methods are used to eliminate/decrease heat loss. The key of the study is a direct comparison that means all conditions are kept the same (3-dimension effects and heat losses are same to both of baseline and sample) except two different materials. Only these two different materials are studied. The conclusion is that annealed pyrolytic graphite has very high thermal conductivity, like diamond, that may be very useful material for thermal applications.

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