ANISOTROPIC GRAPHITE HEAT SPREADERS FOR ELECTRONICS THERMAL MANAGEMENT

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INTRODUCTION

Increasing needs of higher speed and reduced size of electronics in the consumer and industrial markets represent a greater demand on effective and creative thermal management solutions. Although a passive component, thermal management technology has become a vital part of electronics innovations [1]. Electronics whose functionality depends highly on its cooling efficiency include notebook computers, high-end CPU chipsets, power conversion devices, and communication equipment.

Typical thermal management systems consist of external cooling mechanisms, heat dissipaters, and thermal interfaces. The primary function of the heat dissipaters, e.g. heat sinks, is to create the maximum effective surface area where heat is transferred into and carried away by the external cooling medium. Performances of a heat dissipater are conventionally characterized by its intrinsic thermal conductivity, physical surface area, and pressure drop (or drag) coefficient [2]. An additional variable, namely heat spreading coefficient (α), is introduced in this paper through a simplistic computer simulation. The heat spreading coefficient has to be considered when the heat dissipater is a thermally anisotropic material.

Computer simulation was performed to characterize the heat conduction pattern in a flat plate of anisotropic and isotropic materials. Heat flux patterns and temperature profiles in thermal interfaces are visualized at various anisotropy ratios. The sensitivity analysis is used to evaluate the variation of temperature distribution in a flat plate with a point (localized) heat source. Effectiveness of heat transfer through isotropic and anisotropic thermal interfaces is quantified in terms of the heat spreading coefficient. The design concept of using anisotropic materials as thermal interface and heat spreader as part of electronics cooling systems is introduced in this paper.

eGraf^{TM} flexible graphite, a unique material derived from natural graphite flake, is an excellent heat conductor with anisotropic characteristics. eGraf sheets are a proven thermal interface in the electronics industry because of the very high thermal conductivity and excellent surface conformability. Additionally, eGraf can be transformed into a wide spectrum of physical structures, which exhibit a broad range of anisotropy ratio, for specific application requirements. The high degree of thermal anisotropy reduces the temperature gradient in the plane of the sheet and increases the effective heat transfer area, characteristics that are most desirable for electronics with high heat-intensity components. This paper highlights the anisotropic nature of flexible graphite in comparison to isotropic materials such as metals and polymeric compounds commonly used in the electronics industry.

THERMAL ANISOTROPY FUNDAMENTALS

The Fourier law states that the conductive heat flux (Q/A) is proportional to the temperature gradient ($\partial T/\partial L$) in an object [3], i.e.,

$$\frac{Q}{A} \propto \frac{\partial T}{\partial L} \qquad \text{or} \qquad Q = kA\,\frac{\Delta T}{\Delta L} \ \text{(in a finite form)} \qquad \text{Eq. (1)}$$

The proportional constant, k, in Eq. (1) is defined as the thermal conductivity of an object in the direction of heat flow. Equation (1) is commonly used to calculate the thermal conductivity given the temperature difference (ΔT) between two points separated by a known distance (ΔL).

The thermal transfer phenomenon is more complex when the streamlines of heat flow in an object are not parallel to each other. This may be the result of an irregular object boundary, or a heat flow that is not in line with the object's geometry, or the material being anisotropic. In such cases, the thermal transfer characteristics are more complex and should be considered using the 3-dimensional heat transfer equation as expressed by Eq. (2).

$$\rho C_p \frac{\partial T}{\partial t} = k_x \frac{\partial^2 T}{\partial X^2} + k_y \frac{\partial^2 T}{\partial Y^2} + k_z \frac{\partial^2 T}{\partial Z^2} \qquad \text{Eq. (2)}$$

where k_x, k_y, and k_z are thermal conductivity in the x-, y-, and z-directions, respectively.

When all values of k are the same, i.e. the thermal conductivity is independent of the direction of the heat flow and the orientation of the object, the material is thermally isotropic. This is the case for most metals and silicone-based components. When thermal conductivity in at least one direction differs from the others, materials are anisotropic. Two primary examples of such materials are graphite and mica. Anisotropic components are unique for numerous thermal applications because they can be used to direct or alter the heat flow patterns in an object for specific design and service criteria. Particularly, modification of thermal anisotropy for heat sinks and heat spreaders can lead to significant improvement on the cooling effectiveness.

RESULTS AND DISCUSSION

Figures 1a and 1b demonstrate the effects of thermal anisotropy on the heat flow pattern in an extremely simplistic configuration. The heat flux considered in the computer simulation is 20 W/in^2, heating surface area is 2 cm^2 on the lower center surface, temperature of ambient cooling air is 30°C, heat transfer coefficient on upper and side surfaces is 200 W/m^2°C, and the dimensions of the object are 10 cm wide and 0.2 cm thick. The simulation was conducted in a two-dimensional nature with assumptions. First, it was assumed that distortions of temperature profiles and heat fluxes near the edges are negligible and do not influence the validity of the conclusions. Second, the thermal contact resistance between the simulated object and the heat generator was not considered. It should be noted, however, that the thermal contact resistance can be of the same order of magnitude or even higher than the through-body thermal resistance.

Figure 1a shows the simulation of the heat flow pattern and temperature distribution in a plate with $k_{x\text{-}y}$ (i.e. k_x or k_y, thermal conductivity in the X-Y plane or in the "x" direction in the figures) of 250 W/m°C and k_z (i.e. thermal conductivity in the Z direction or in the "y" direction in the figures) of 7 W/m°C. Arrows and colors in Figure 1a represent the vectors of heat flow and temperature. Temperature contours are also included in the figure to facilitate the recognition of the temperature profile in the simulated object. Similar heat transfer characteristics of a plate with $k_{x\text{-}y}$ of 400 W/m°C and k_z of 5 W/m°C is shown in Figure 1b. Figures 1a and 1b illustrate the heat spreading pattern of thermally anisotropic materials. A significantly high degree of heat spreading takes place in the bottom of the plate. Consequently, the maximum temperature variation, i.e. the temperature difference between the hottest and coldest spots, on the upper surface of the plate is reduced compared to that of an isotropic plate as shown in Fig. 2. Heat spreading still takes place in an isotropic plate, but at a much lower magnitude, which is evidenced by the fact that all temperature contours are fairly parallel with each other.

The XY to Z anisotropy ratio for materials simulated in Figures 1a, 1b and 2 are of 36, 80 and 1, respectively. The heat spreading coefficient (α), a dimensionless variable, is defined by Eq. (3) to quantify the effect of thermal anisotropy on the magnitude of heat spreading.

$$\alpha = \frac{Max.\,\Delta T_{top}}{Max.\,\Delta T_{bottom}} = \frac{(T_{top}^{\max} - T_{top}^{\min})}{(T_{bottom}^{\max} - T_{bottom}^{\min})} \qquad \text{Eq. (3)}$$

The temperature values at the four locations of the plate used to determine (α) are indicated in the figures. The heat spreading coefficient for materials of Figs. 1a, 1b and 2 are 1.42, 1.88 and 1, respectively. It is clear that the heat spreading efficiency increases with the thermal anisotropy ratio. Equation 3 also suggests that the heat spreading coefficient for an ideal heat pipe can approach infinity. It is also important to note that the value of α depends greatly on the geometry. When the heating and cooling surface areas of the plate are the same, α equals unity regardless whether the material is isotropic or anisotropic.

Values of the heat spreading coefficient for isotropic materials can be found or calculated conveniently from charts in several thermal handbooks, such as Kennedy Chart [4]. However, systematical charts for anisotropic materials are rare and quite often values of α at specific conditions and geometry can only be obtained through computer simulation. There is a need to further explore the use of anisotropic materials for electronics cooling applications. The heat spreading coefficient, in addition to the thermal conductivity, surface area, and drag coefficient, needs to be considered when the performance of a heat dissipater is assessed.

CHARACTERISTICS OF eGRAF^{TM} HEAT SPREADERS

Graphite is a crystalline form of elemental carbon. It is gray to black in color, opaque, soft, and has an earthy to metallic luster. The carbon atoms in graphite are arranged in layers of hexagonal rings. The carbon-carbon bonds within the layers are quite strong, while the forces between the layers are relatively weak. These two types of bonds cause graphite to be highly anisotropic, or directional, in its properties. Thermal conductivity of graphite crystal is as high as 1600-2000 W/m°C in the plane and 4-9 W/m°C through the plane [5]. eGraf is derived from natural graphite flake [6], and therefore possesses thermal and electrical anisotropy characteristics similar to those of the single graphite crystal.

Table 1 lists typical properties of eGraf materials. These properties can be modified to suit a wide range of uses. eGraf is thermally stable and is not combustible or ignitable. It shows excellent conformability to rigid surfaces at low compressive loads, and various degrees of compressibility and resiliency. In short, eGraf flexible graphite possesses all the critical features required for an excellent thermal interface for electronics cooling systems.

eGraf flexible graphite is an equally feasible material as a heat spreader and heat sink for electronics cooling applications. The thermal anisotropy of eGraf flexible graphite is a unique characteristic that most commonly used metals and elastomeric compounds do not possess. Figures 1a, 1b and 2 clearly demonstrate that fundamentally there are a number of benefits and advantages to incorporating the concept of thermal anisotropy into the design considerations for advanced thermal systems. The thermal anisotropy ratio of eGraf materials ranges from 5 to 50, which represents a wide range of flexibility and maneuverability for thermal system designs. The stress-strain curve shown in Figure 3 reveals that eGraf materials are fairly compressible under very low load (less than 100 psi) and still maintain their mechanical integrity at extreme compression (over 4000 psi). The range of eGraf features and properties creates an additional dimension for the practical thermal management of electronics.

Computer simulations reveal that the effective heat transfer area and the overall heat transfer rate increase by more than 10 times when the thermal anisotropy ratio is over 15 for certain geometries. Integration of thermally anisotropic materials into conventional thermal solutions optimizes the cooling effectiveness and temperature uniformity functionality. This effect is particularly significant in cases where the physical dimension of the system restricts heat dissipation, or where heat is generated within a confined area or at multiple locations.

CONCLUDING REMARKS

Computer simulation was performed to characterize the temperature profile and heat flux pattern in a flat plate. Heat dissipation characteristics of anisotropic thermal materials were assessed in comparison with that of isotropic ones. The advantage of using thermally anisotropic materials for maximizing the cooling effectiveness, in terms of reducing temperature variation and reducing component surface temperature, was discussed for applications involving a point (or multiple localized) heat source. Simulation results revealed that materials with high degrees of anisotropy significantly improve the effectiveness of heat dissipation and reduce the temperature variation. An isotropic material is rather ineffective in dissipating heat from a localized heat surface.

Computer simulation demonstrated that anisotropic materials exhibit a unique thermal conduction behavior that can be applied for “directing” heat flows and “maneuvering” temperature profiles. Depending upon specific design and service criteria, materials with certain degrees of thermal anisotropy should be used to optimize the overall heat dissipation performances. This study led to a conceptual change in the development of advanced thermal management solutions for smaller, faster and more powerful electronic systems with critical thermal dissipation problems.

References

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Table 1. Typical Thermal and Mechanical Properties of Basic eGraf™ Materials

Properties	Ranges	Remarks
Thermal Conductivity (W/m°C) X-Y (in-plane) direction Z (through-plane) direction	 100 – 250 5 - 20	Thermal anisotropy ratio adjustable from 5 to 50
Thermal Contact Resistance (°C•in^2/W)	< 0.05	Contact resistance reduced with compression load; measured within 15-50 psi
Coefficient of Thermal Expansion (CTE) X-Y and Z directions	-0.4×10^{-6} m/m/°C 27×10^{-6} m/m/°C	Direction-dependent CTE; alterable
Tensile Strength (psi)	> 1,000	ASTM F-152
Compressive Strength (psi)	> 35,000	ASTM C-695
Modulus of Elasticity (psi)	0.2×10^5	Typical value
Young’s Compressive Modulus (psi)	27,000	Typical value

Figure 1a
Temperature Profile and Heat Flow Pattern in an Anisotropic Object (kx = 250 W/mk; ky = 7 W/mk)

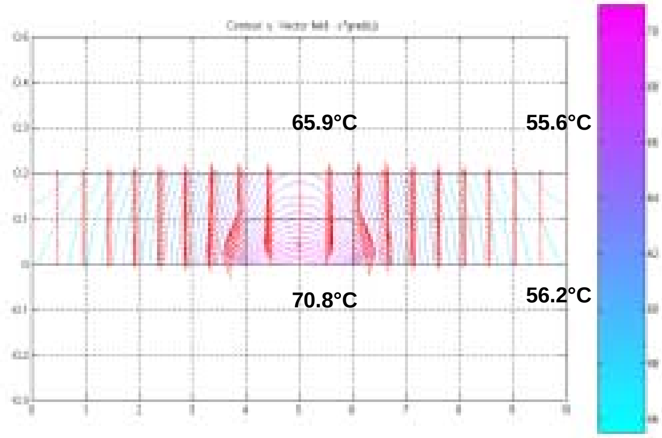


Figure 1b
Temperature Profile and Heat Flow Pattern in an Anisotropic Object (kx = 400 W/mk; ky = 5 W/mk)

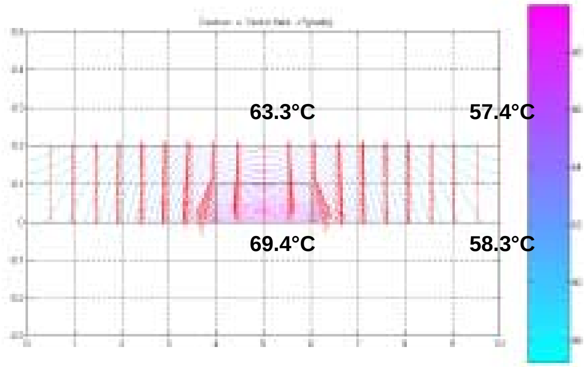


Figure 2
Temperature Profile and Heat Flow Pattern in an Isotropic Object (kx = ky = 150 W/mk)

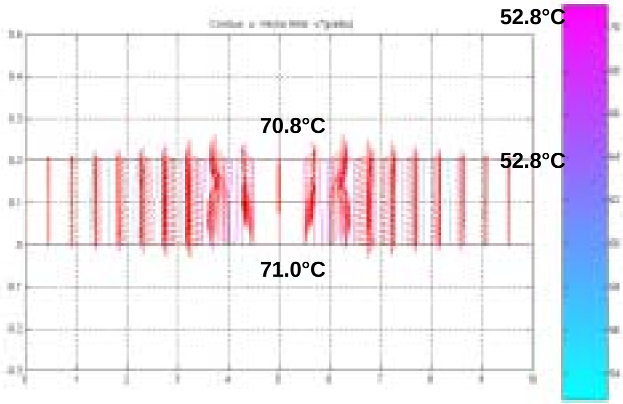
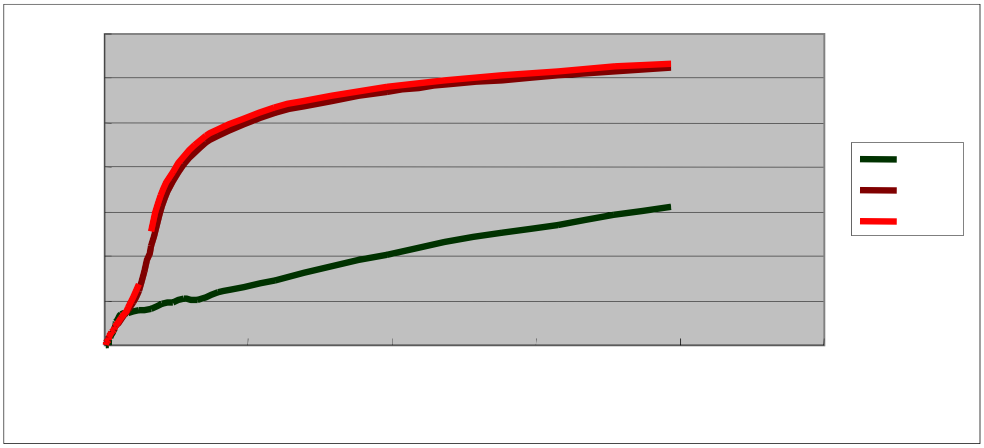


Figure 3
Strain-Stress Characteristics of GRAFOIL® Flexible Graphite



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