Rigorous Reliability Testing of an Encapsulated Thermal Pyrolytic Graphite (TPG) Heat Spreader for Passive Thermal Management Applications

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Abstract
Continued microelectronic miniaturization has resulted in higher power density, increasing the need for high performance thermal management. One possible solution for board-level thermal management is to fully encapsulate a high thermal conductivity material, such as Thermal Pyrolytic Graphite (TPG®; ~1700 W/mK) in a metal (such as 6061 aluminum alloy), producing an efficient passive heat spreader for thermal dissipation. The metal shell provides sufficient mechanical strength at a small detriment to the overall thermal conductivity. Reliability and consistent performance over time are critical for thermal management systems, especially in Defense and Aerospace applications. MIL-STD-883H provides test parameters for reliability involving exposure to mechanical shock (Method 2002.5), mechanical vibration (Method 2005.2), and thermal shock (Method 1011.9), with traditional evaluation criteria involving microelectronic device performance and/or a visual examination. For this work, the reliability of aluminum encapsulated TPG® test coupons were evaluated with more demanding criteria: a visual examination, X-ray inspection, acoustic microscopy, and thermal conductivity performance testing, both before and after the previously discussed MIL-STD-883H exposures. The encapsulated coupons showed excellent robustness; the thermal conductivity properties remained constant with an average value around 965 W/mK, and the non-destructive imaging revealed excellent bond quality for the metal encapsulation, with no evidence of delamination. This more stringent evaluation criteria after MIL-STD-883H testing provides a better way to evaluate the reliability of passive thermal management systems. The study results demonstrate the metal encapsulated TPG® heat spreader as a superior thermal management solution, enabling greater power dissipation than typical aluminum and copper heat sinks and demonstrating high reliability surpassing that of industry standard testing.

Key words
Heat spreader, passive cooling, thermal management, thermal pyrolytic graphite, shock, vibration, non-destructive imaging

I. Introduction
Thermal Pyrolytic Graphite (TPG®) is a unique synthetic material produced by Momentive Technologies containing millions of layers of highly-oriented graphene planes. It is both lightweight (2.3 g/cm3) and extremely thermally conductive in its X-Y basal planes (~1700 W/mK) [1]. This material is utilized in an aluminum encapsulant to create the TC1050® heat spreader for board-level cooling applications [2].

Reliability and longevity of these passive heat spreaders are critical, as most installations are in aircraft, satellite, radar, telecommunication, and other high value, extreme environment products. Microelectronic components for similar applications are typically tested according to Department of Defense specification MIL-STD-883H, which outlines environmental testing protocol, such as mechanical shock, mechanical vibration, and thermal shock [3]. This standard is for microcircuits though; for passive components such as TC1050®, it does not outline any post-test examination beyond visual inspection.

Many non-destructive imaging techniques exist that may be good candidates to examine passive parts after MIL-STD-883H testing. Scanning acoustic microscopy (SAM) is one that is uniquely capable of imaging the interface between two bonded materials [4]. SAM is a known technique in industry for examining the quality of diffusion bonds, since it can expose voids, bubbles, delamination, etc. at the interface [4,5]. In addition, a traditional X-ray image would also provide non-destructive imaging that would reveal voids, delamination, etc., albeit with a lower resolution than provided by SAM.

In conjunction with the examination of bond integrity with these non-destructive imaging techniques, performance testing of passive components before and after environmental exposure would verify consistent performance in the field.

In this work, TC1050® coupons made from TPG® tiles encapsulated in 6061 aluminum alloy were tested for mechanical shock, mechanical vibration, and thermal shock according to MIL-STD-883H, and then evaluated using thermal conductivity (for application performance) and non-destructive imaging (for bond integrity). This more rigorous evaluation protocol coupled with MIL-STD-883H testing provides more confidence in a passive component's ability to survive without degradation in harsh aerospace and defense applications.

II. Materials and Methods

Tiles of TPG® were encapsulated in 6061 aluminum alloy and machined to form coupons for testing, roughly 5" long x 2" wide x 0.125" thick (see Fig. 1 below). Multiple coupons were manufactured to provide better statistics.

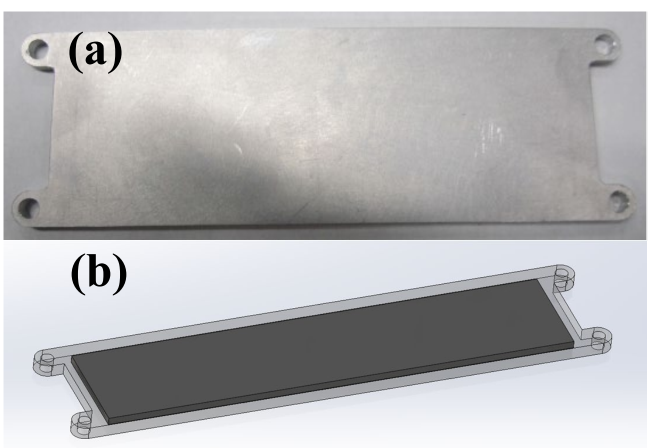

Figure 1: Photograph showing the test coupon of TC-1050® (a), as well as a schematic drawing of the same coupon with the TPG® tile visible (b).

A. In-plane Thermal Conductivity Testing

In-plane thermal conductivity was measured using a lab-constructed setup (see Fig. 2). The apparatus consisted of a hot side (copper blocks thermally coupled to a resistance heater) and a cold side (copper blocks thermally coupled to a chiller). The TC1050® coupons were thermally mated to a copper plate using thermal paste. The cross-sectional area of the coupon and the copper plate were known. Two thermocouples were attached to both the copper plate and the test coupon (4 thermocouples total), and the distance between them was measured. The test cell was then wrapped in insulation to minimize the heat losses to the surrounding environment. After the system reached thermal equilibrium, the heat flux of the system was calculated using the thermocouples on the copper plate, the known value of thermal conductivity for copper (398 W/mK), and the equation,

$$q = {-\lambda \Delta T}/{\Delta x} \quad (1)$$

where q is the heat flux (W/m^2), λ is the thermal conductivity (W/mK), ΔT is the change in temperature between the two thermocouples, and Δx is the distance between the two thermocouples. Using the heat flux q, and the same Eq. 1, the in-plane thermal conductivity of the test coupon (λ) can be calculated using the temperature difference from the thermocouples on the test coupon (ΔT_{sample}) and the distance between the thermocouples (Δx_{sample}).

The test setup provided a good measure of real-world performance, by measuring the ability of the TC1050® coupons to conduct heat. Additionally, it showed the required repeatability to benchmark multiple samples before and after testing.

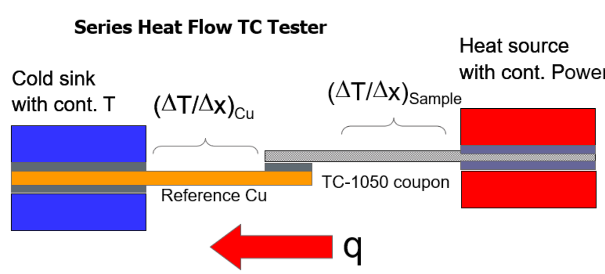

Figure 2: Schematic showing the experimental setup for the inline thermal conductivity testing.

B. Environmental Testing

Test coupons were tested for mechanical vibration (MIL-STD-883H Method 2005.2) and mechanical shock (MIL-STD-883H Method 2002.5) at Tektronix (North Billerica, MD), a DLA certified test lab. For mechanical shock testing, the parts were fixed to a test fixture and subjected to 500G force for 1.0 milliseconds. Each axis was tested for a total of 6 shocks. Mechanical vibration testing had the parts similarly attached to a fixture and a 60 Hz, 20G sine wave force is applied for 32 hours. The parts were then rotated with the test repeated two additional times, to test 3 axes in total.

Test coupons were tested for thermal shock according to MIL-STD-883H Method 1010.8 Level C by Keystone Compliance (New Castle, PA), also a DLA certified test lab. The parts were cycled between -65°C and 150°C for 30 minutes each cycle, for a total of 10 cycles.

C. Non-Destructive Imaging (X-ray and Scanning Acoustic Microscopy)

Non-destructive imaging was conducted at SMART Microsystems (Elyria, OH) using a Nordson XD7600NT Diamond X-ray Inspection System, and a Sonoscan scanning acoustic microscope (SAM). The SAM images were acquired from a reflective scan at the two interfaces between the 6061 aluminum alloy and the TPG®.

D. Test Protocol

After the coupons were machined, an initial visual exam, thermal conductivity measurement, and non-destructive imaging (X-ray and SAM) were conducted. After verifying all bond integrity, the mechanical shock and mechanical vibration testing was conducted. The coupons were subsequently examined visually and with non-destructive imaging. The same coupons were then submitted for thermal shock testing, followed by a final visual examination, non-destructive imaging, and thermal conductivity testing.

III. Results and Discussion

A. Visual examination

After the environmental testing, no visual change was observed. The bond line was intact, with no indications of delamination.

B. Non-Destructive Imaging (X-ray and Scanning Acoustic Microscopy)

After initial machining, prior to any testing, the coupons exhibited excellent bonding with no evidence of voids or delamination (see Fig. 3 below for an example).

Similar imaging was performed after both mechanical shock and mechanical vibration testing (see Fig. 4 for an example) and after subsequent thermal shock performed on the same coupons (see Fig. 5 for an example). Again, good bond quality was maintained, with no evidence of voids or delamination present. The TC1050 part did not suffer any interior damage and the TPG tile remained intact.

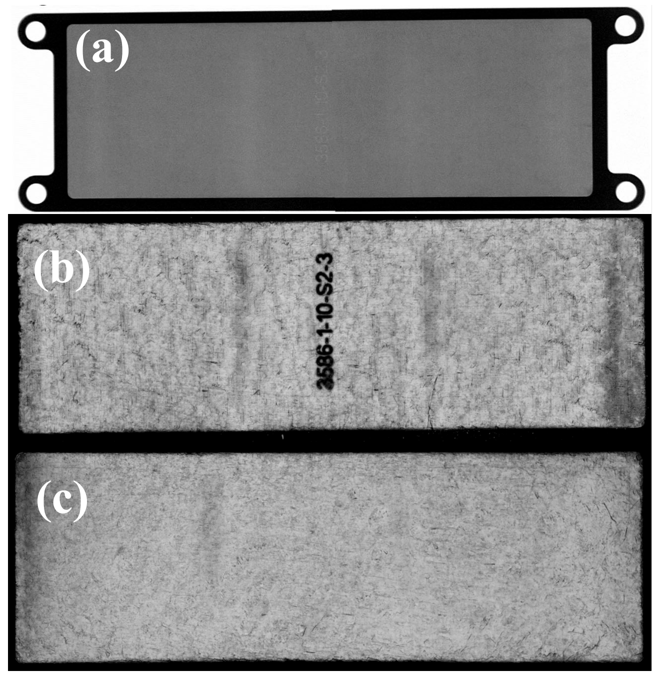

Figure 3: Images of a single coupon in the "as-machined" condition, showing the (a) X-ray image, and the top (b) and bottom (c) interfaces revealed by the scanning acoustic microscope.

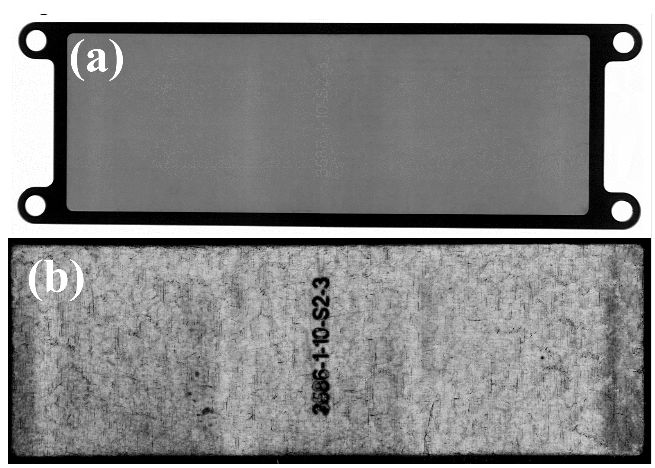

Figure 4: Images of a single coupon after mechanical shock and mechanical vibration testing, showing the (a) X-ray image, and the top (b) and bottom (c) interfaces revealed by the scanning acoustic microscope.

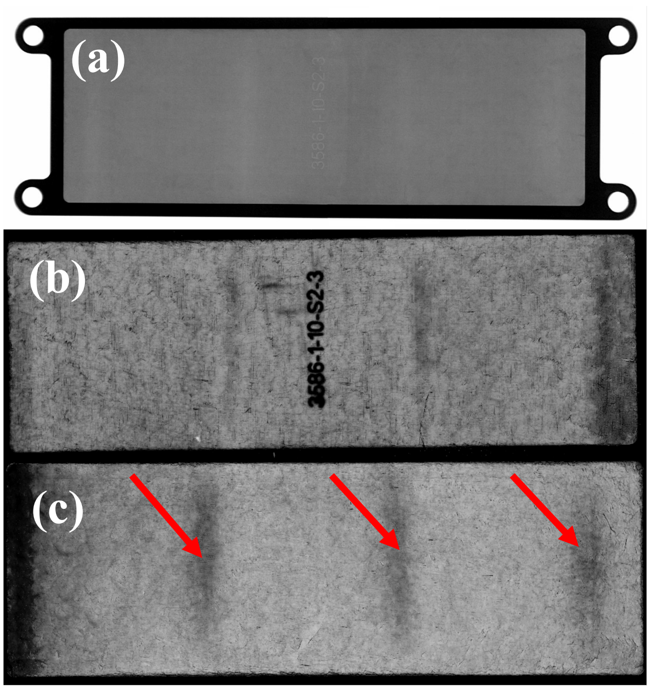

Figure 5: Images of a single coupon after mechanical shock, mechanical vibration, and thermal shock testing, showing the (a) X-ray image, and the top (b) and bottom (c) interfaces revealed by the scanning acoustic microscope. The hazy vertical shadows (shown by red arrows) were imaging artifacts, not a defect.

C. *In-plane Thermal Conductivity Testing*

No significant change in the in-plane thermal conductivity was observed for the samples when comparing before and after all the MIL-STD-883H testing (see Fig. 6). A paired t-test of the sample population results gives a T-value of 0.39 and a P-value of 0.71, suggesting there is no significant statistical difference in the thermal conductivity of the test samples. These results demonstrated that the application performance of the coupons was unchanged after undergoing mechanical shock, mechanical vibration, and thermal cycle testing.

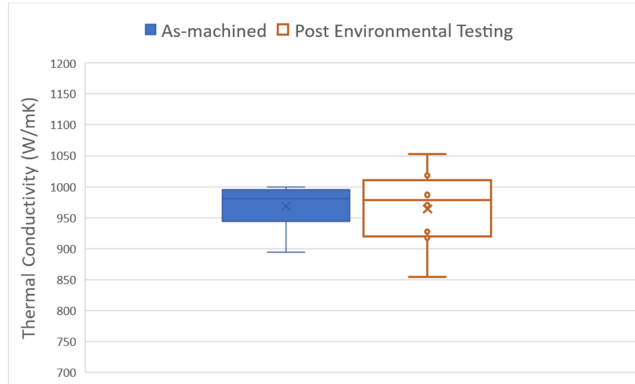

Figure 6: Box plots showing the thermal conductivity results for the coupons before testing ("As-machined", left solid blue plot) and after all environmental testing ("Post Environmental Testing", right, outlined plot).

IV. Conclusion

After MIL-STD-883H environmental testing, the TC1050® coupons showed no change in performance, as shown by the constant in-plane thermal conductivity. In addition, the bond integrity of the 6061 aluminum alloy encapsulant was also maintained through the mechanical shock, mechanical vibration, and thermal shock testing, as revealed by the X-ray and scanning acoustic microscopy imaging. This more rigorous testing protocol combining performance testing and non-destructive imaging could be used as a template to test similar passive components for defense and aerospace applications.

Acknowledgment

The authors would like to thank Kraig Holler and other members of SMART Microsystems (Elyria, OH) for performing the X-ray and scanning acoustic microscopy imaging.

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