AVIONICS COMPOSITE EVALUATION

B.J. Sullivan and J.C. Houston
Materials Research & Design and Amoco Polymers

Abstract

Designers of electronic systems for current and next generation missiles systems are placing more emphasis on reduced weight, increased functionality and improved reliability. With the advent of large scale integration and multi-chip modules, packaging engineers are rapidly reaching a point where more electronic components can be integrated into electronic systems than what can be effectively cooled by traditional metal materials. This has resulted in the development of an increasing number of new composite materials that can provide improvements over conventional packaging materials. These improvements include better thermal management, higher strength and stiffness, and significant weight savings.

One composite material constituent being investigated to address these future requirements is high modulus pitched-based graphite fibers. These fibers exhibit thermal conductivity of up to three times that of copper in the fiber direction, are light weight and have a very low coefficient of thermal expansion (CTE). These fibers can be combined with a number of different matrix materials such as polymers and metals, depending on the specific application. This paper focuses on the implementation of high modulus pitch-based graphite composites into two areas of missile avionics, chassis covers and printed wiring board (PWB) thermal plane/constraining cores. For these two applications, a significant weight savings was realized, thermal performance improved and mechanical integrity maintained by replacing aluminum with pitch-based graphite fiber reinforced organic matrix composites.

Nomencalture

PWB	Printed Wiring Board
CTE	Coeffecient of Thermal Expansion
CCA	Circuit Card Assembly
ACE	Avonics Composite Evaluation
PTH	Plated Through Holes

Background

The objective of the ACE Program was to demonstrate the feasibility of replacing existing aluminum components on a select missile avionics chassis with high modulus/high thermal conductivity composite materials. Chassis covers and PWB thermal plane/constraining cores were identified for replacement. The goals set forth by the program were 1) to reduce the weight of the selected components by 40%, 2) improve thermal performance, 3) maintain mechanical design margins of safety and 4) meet the form, fit and function of the existing aluminum components.

Composite Cover Design and Analysis

The design of the composite chassis cover was driven by the requirement to maintain interchangeability (form and fit) with the aluminum baseline. Internal design and construction was not constrained. The chassis cover is an integral structural member of the assembly and houses the ethylene glycol and water mixture coolant required for active cooling of the chassis during ground testing of the device prior to operation.

The composite design consists of two pitch fiber (Amoco's K-1100) reinforced cyanate ester matrix composite assemblies (.16 and .08 inch thick) bonded together to form a pressure-tight flow through cover. As shown in Figure 1, the serpentine coolant flow path was cut into the .16 inch thick composite. Cutouts were also made in the non-structural areas of the 0.16 inch thick assembly to reduce weight. For the top cover, coolant entered the rear side of the chassis and serpentined through the cover and exited out the power supply side of the chassis. The flow path was the reverse of that for the bottom cover.

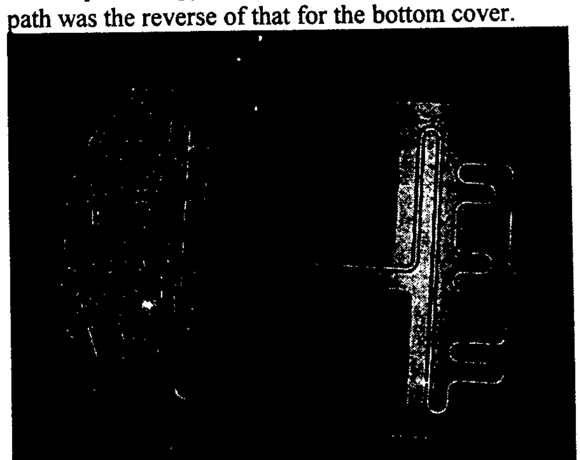

Figure 1. Top Cover with Channels

Provisions for mechanical interface hardware (fasteners and coolant fittings) were provided on the composite covers..

A finite element heat transfer model of the cover was generated. Results from the analysis were used in the internal design of the cover. The serpentine flow path was optimized to provide a sufficient quantity of coolant such that the current aluminum cover thermal performance was achieved and the desired pressure drop was maintained. The comparison in thermal performance between the baseline aluminum cover and composite cover is provided in Table 1 for a simulation of ground-ops testing. The aluminum results in Table 1 are measured data. The K-1100/CE column is analytically predicted after first reproducing the aluminum cover results using the same finite element heat transfer model.

Table 1.
Thermal Comparison (°C)

Location	Al (Baseline)	K-1100/CE
Cold Plate Center	20.1	20.8
Cold Plate Rt Sidewall	22.9	21.5
Rt Sidewall	24.8	23.4
Rt Sidewall	24.6	24
Cover-Rt Mux	22.4	20.9
Cover Pwr Supply	23.3	21.6
Cover Ft Connector	21.6	21.9
Cover Rear Connector	22.6	22

Similarly, a finite element stress analysis model was generated in order to calculate cover stresses for static equivalent 'G' loads and for the internal pressure from the coolant. The stiffer K-1100/CE composites provided a significant improvement in the mechanical performance of the covers by increasing the first natural frequency from 1560 Hz to 2352 Hz. For most of the random base acceleration loadings, this leads to a significant reduction in the composite cover stresses since random excitations for frequencies lower than 2350 Hz will not be amplified for the composite component. A comparison of analytically predicted stress and deflections in the aluminum baseline and K-1100/CE covers is provided in Table 2. Note that the finite element model has been verified through comparison of predictions with measurements made on the aluminum baseline cover.

Table 2.
Structural Analysis Results

Load Case	Al (Baseline)	K-1100/CE
Ground Ops Thermal		
Stress (psi)	2000	1800
Deflection (in)	.00022	.00219
70 Gxy Launch		
Stress (psi)	520	534
Deflection (in)	.00052	.00051
70 Gz Launch		
Stress (psi)	392	200
Deflection (in)	.00036	.00011
First Mode (Hz)	1560	2352

Pressure Testing

Nine composite covers were fabricated and 6 were pressure tested. The purpose of the pressure testing was to reduce risk by determining the effects of long term exposure on the composite material to ethylene glycol/water coolant under worse case pressure load conditions. All 6 passed the pressure test without pressure loss or failure. In addition to the pressure testing, a separate set of specimens successful completed long term exposure to ethylene glycol without deterioration of mechanical properties.

The aluminum baseline cover weighs 1.01 pounds. Average weight of the composite covers was .53 pounds. This equates to greater than a 40% weight savings.

Conclusion

Four composite chassis covers were completed and installed on existing aluminum chassis. The assembled aluminum chassis with the composite covers were delivered to the system integrator in June 1998 in preparation for a series of environmental tests. Figure 2 is a photo of an assembled aluminum chassis with the installed composite covers.

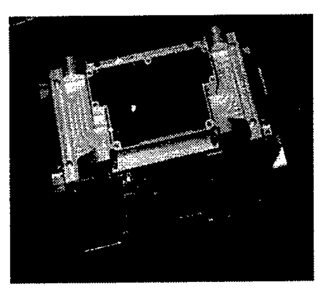

Figure 2. Full Chassis with COI composite cover

All goals established by the program were met or exceeded. Greater than a 40% weight savings was achieved while maintaining form and fit interchangeability with the aluminum cover chassis. Structural performance is predicted to be equivalent or superior to the baseline design. The current testing is expected to confirm these predictions.

PWB Design

The existing PWB design is a double sided board consisting of an aluminum core bonded between two active circuit card assemblies (CCAs). The aluminum core is needed for conductive heat transfer and mechanical stiffness. Because this CCA is used in a missile application, weight, structural stiffness and reliability are of paramount importance. Electrical interconnect between the two active CCAs is accomplished with a flexible circuit wrapping around one edge of the assembly. Figure 3 represents a layout of the assembly.

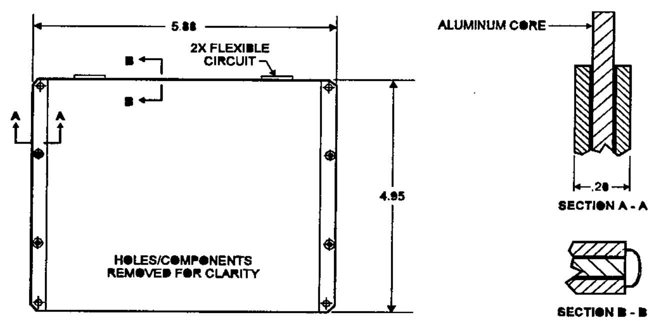

Fig. 3. Existing PWB Layout

This type of assembly would be called a double sided, non-integral core. Non-integral is defined as no vias (holes) or electrical connections made through the core. An integral core would interconnect the top and bottom CCAs directly through the core.

The design approach was to replace the aluminum core with pitch-based graphite fibers in an organic matrix and take full advantage of the integral core approach. This approach would alleviate the requirement for the external flex circuit interconnect and in addition save 40% of the weight per double sided PWB without degrading the thermal properties of the design. A secondary benefit of the composite core is that the use of 'J'-leads are no longer required. Currently, active components are attached to each PWB using 'J'-leads to account for the CTE mismatch between the ceramic components and the substrate. This mismatch no longer exists with a composite core so cost, weight and volume savings associated with deletion of 'J'-leads can be exploited.

Numerous materials were investigated for use as PWB circuitry substrates, final lamination adhesive and core hole fill. To facilitate in the selection of these materials, extensive testing was performed at the coupon level.

Interlaminar shear between the core/substrates and between the individual layers of the core was the first problem solved by testing numerous coupons. A finite element math model approach was used to help predict interlaminar shear stresses in the composite core assemblies. This data was used to aid in developing a robust and reliable design.

Using the best combination of materials, 8 test PWBs were fabricated. To simulate the effects of copper circuitry, a checker board artwork pattern was implemented. Ground planes were simulated with 80% copper and typical circuit planes used 13% copper. Two types of substrate dielectric materials were used; Kevlar/polyimide and glass/polyimide. Eight 8-layer substrates (2 required per double sided PWB) were fabricated out of each dielectric material type. Four Kevlar/polyimide and four glass/polyimide double sided, multi-layer, integral composite core PWBs were fabricated for a total of 8 test articles. To test the robustness of the plated through holes (PTHs), 100 PTHs ranging from 0.020 to 0.040 were equally spaced throughout the PWB. The final overall PWB thickness measured 0.150" (typical); 0.040" composite core, 2 substrates @ 0.045" each and 2 final lamination adhesives @0.010" each. Fig. 4 is a layout of the test PWB.

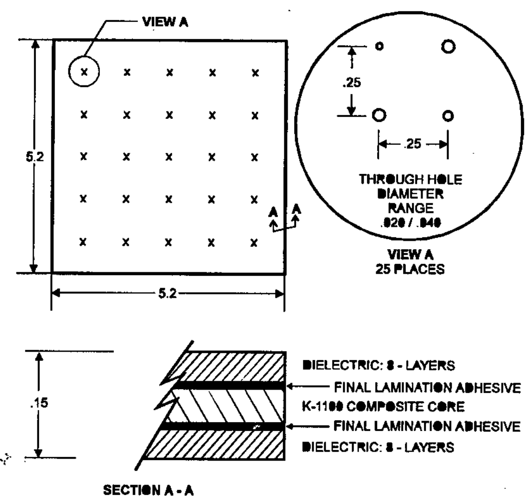

Fig. 4. Test PWB Layout

Testing

Testing of the 8 PWBs focused on surface CTE and PWB reliability as a function of temperature. In order to eliminate the need for 'J'-leads, it is recommended that the surface CTE be between 4 and 8 PPM/°C. This minimizes the ceramic component/PWB substrate solder joint stress and hence maximizes solder joint reliability. As the surface CTE extends outside these limits and/or the temperature extremes increase, solder joint reliability (thermal cycles to failure) decreases. Table 3 lists the measured in-plane surface CTE of test PWBs.

Table 3.
PWB Surface CTE

Kevlar/polyimide	Glass/polyimide
(PPM/°C)	(PPM/°C)
4-5 In Plane	6-8 In Plane

PWB Reliability

The PWB test coupons were subjected to four different temperature cycles (Table 4), simulating an interceptor missile environment. Temperature cycling was used as a means of stressing the PWB's because the CTE mismatch between the core and the substrates can develop high stresses which can cause delaminations or fatigue failures in PTHs. For this test, PWB reliability was verified by measuring DC continuity of each of the 100 PTHs and also visually inspecting for delamination of the core and the interface between the substrate and the core (final lamination adhesive). The four thermal cycles were run sequentially on the same coupons.

Table 4.
Thermal Cycling Profiles

Profile #	1	2	3	4
Temp. °C	-40/100	-46/55	-28/38	-65/125
Cycles	60	120	1340	200
Hrs/Cycle	2.4	1.9	1.6	2.5

A thermal shock environment (Table 5) was added to expedite the thermal cycling schedule and also to evaluate the performance of the test PWBs in a more severe environment.

Table 5.
Thermal Shock Profiles

Profile	1	2	3
Temp. °C	-40/100	-46/55	-28/38
Cycles	60	120	1340
Hrs/Cycle	1.0	1.0	1.0

Coupons subjected to thermal shock testing were separate coupons from those subjected to thermal cycling.

Of the 8 test PWBs, one of each design (Kevlar/polyimide and glass/polyimide) was used as a control and not subjected to environmental testing, two of each design were thermally cycled and one of each design was thermal shocked. Testing was completed sequentially, starting with Profile 1 and concluding with Profile 3. All test PWBs passed the DC continuity test which means there were no PTH failures as a result of either thermal cycling or thermal shock testing. In addition, visual inspection proved that neither the core nor the final lamination adhesive delaminated. Final CTE measurement showed no change in surface CTE before or after exposure to the environment. This indicates that the core has not separated from either substrate.

Accelerated Life Testing

Upon completion of thermal cycle profiles 1 through 3 with no failures, two of the test PWB's were then subjected to an accelerated life thermal profile (Table 4; profile #4). The accelerated life profile provided a wider temperature extreme, which further stressed the PWB's. One Kevlar/polyimide and one glass/polyimide PWB were exposed to 200 cycles. Upon completion of profile #4, the Kevlar/polyimide PWB showed no signs of delamination in the core or final lamination adhesive. Electrical continuity was maintained on all of the 0.040 diameter (50 total) and 0.030 diameter (25 total) PTHs. Four out of 25 randomly spaced, 0.020 diameter PTHs failed continuity. Note that this test PWB had completed thermal cycling profiles 1,2 and 88% of 3 (1354 thermal cycles) prior to the start of accelerated life testing. The glass/polyimide test PWB delaminated after 157 accelerated life cycles. Note that this test PWB also completed thermal cycling profiles 1,2 and 3 (1520 thermal cycles) prior to accelerated life testing.

Figure 5 shows a photo of the PWB containing the K-1100/CE core.

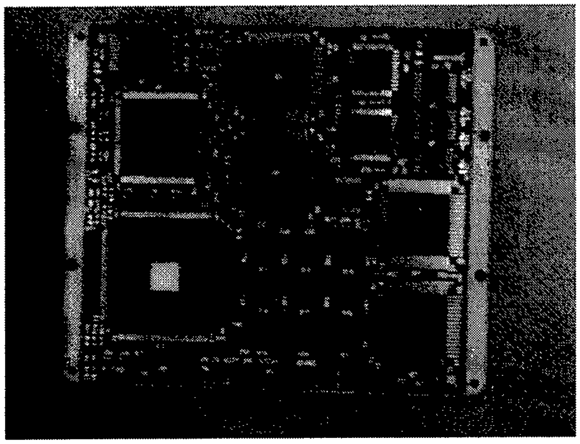

Figure 5. Northrop Grumman PWB unpopulated

Modal Analysis

The first two significant modes of a composite core PWB were empirically measured and are listed in the table below. A dynamic impact hammer test was performed with the PWB mounted in a fixture that simulated the wedge lock interface but did not account for the stiffness added by the edge connector to motherboard interface. In other words, the unit under test represented the following edge conditions: clamped/clamped/free/free. The edge conditions as tested will yield a lower natural frequency than if the edge connector side was supported. Note that this was a bare board test and did not account for the mass of the components which would tend to lower the natural frequency (it is assumed that the components do not add stiffness, just mass). The results of this test showed that the composite core PWB had similar first two modes as the aluminum core PWB (see Table 6).

Table 6.
Natural Frequency Comparison

Aluminum Core PWB	Composite Core PWB
330 Hz	315 Hz
390 Hz	450 Hz

This comparison should only be considered as a first order approximation because the composite core PWBs did not experience the same test environment as the aluminum core PWBs. The two main environmental differences (no components and different edge conditions) have opposite effects on natural frequency. No attempt was made to quantify the impact of each difference.

Weight

The average weight of the composite core test PWB's (Kevlar/polyimide and glass/polyimide) was measured to be 117.8 grams. The baseline aluminum core PWB weight was 193 grams. (All weights were measured without wedge locks). This equates to a 40% weight savings.

Conclusion

The conversion from a double sided, aluminum core PWB to an integral, composite core PWB, proved to be a viable and robust design. The composite core PWB's met all of the established program goals. Surface CTEs for both dielectric materials were lowered to 4 - 8 PPM/°C. Structural integrity of the design was verified through temperature cycling. Form fit and function was not changed and the weight reduction goal of 40% was met. Though thermal conductivity measurements have not yet been performed, laminate analysis calculations of the thermal plane conductivity indicate that thermal performance will also be enhanced due to the increase in conductivity of the pitch based graphite fibers over aluminum.