System Performance of a Lightweight Beryllium Composite Heat Sink for Advanced Electronic Packaging

Tom Parsonage

Abstract

Recent advances in commercial and military electronics have created a need for electronic packaging materials that have thermal cycle reliability over a temperature range of -45°C to +85°C, for increased operational lifetime, plus vibration reliability, while reducing the weight and size of the avionics packaging.

This paper will present the development of a family of beryllium-based metal matrix composite materials which offer the electronic packaging designers an attractive combination of properties to address the increasingly demanding needs of the electronic packaging engineer.

The paper will focus on the system performance improvement by the use of these new materials in applications such as, the IRIDIUM® MCM-L package and various SEM-E electronic modules for aircraft avionics, like the F16 and F22.

Introduction

Recent advances in electronic packaging designs for multichip modules (MCM's) used in spacecraft electronics, and standard electronic modules for aircraft avionics (SEM-E), have created a need for substrate materials that must have improved fundamental characteristics such as: high thermal conductivity (TC), low weight, high stiffness, improved thermal cycle reliability over broad temperature ranges, and a coefficient of thermal expansion (CTE) that ideally matches the components installed in the package or helps in constrainment of the total package in order to minimize the thermal mismatch of the printed wiring board (PWB) materials and the packages. These advanced packaging designs also need materials to accommodate increased power demands, while enduring the harsh environments of military applications.

To address those needs, Materion Beryllium & Composites has developed a family of lightweight beryllium based metal matrix composites. This family of materials, called E Materials (grades E20, E40, E60) offers a range of tailor able properties and a significant improvement over other electronic packaging materials, such as copper moly copper (CMC), AlSiC, CuW, Kovar, and aluminum, in meeting the thermal performance needs of MCM's SEM-E's, to R/F and digital microwave packages.

Material Description

The beryllium metal matrix composites consist of a fine single crystal Beryllium Oxide (BeO) platelet surrounded by a continuous beryllium (Be) matrix. The volume fraction of the BeO in the matrix is altered, 20-60%, to tailor the thermal and mechanical properties, as well as the density of the composite, see Table 1. Unlike many of the new advanced thermal performance materials, the properties of the beryllium composites, E Materials, are isotropic and thermally stable.Ref.1 The resulting composites exhibit a high modulus, good thermal conductivity, low density, and a lower CTE.

Table 1 summarizes the various properties of selected materials that may be used for these types of applications.

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Table 1 – Materials and Their Properties for Microelectronic Packages

Material	Density g/cc (Lbs/in³)	E-Modulus Gpa(Msi)	Thermal Conductivity W/m/K	CTE ppm/°C Avg 25°-50°C
Be/BeO Composites				
• E20	2.06 (.075)	303(44)	210	8.7
• E40	2.30 (.084)	317(46)	220	7.5
• E60	2.52 (.091)	330(48)	230	6.1
AlSiC-70%	3.01 (.111)	220(32)	~170	6.7
AlSiC-45/55%	2.95 (.109)	195(28)	160	8.5
Kovar	8.1 (.300)	140(20)	14	5.9
CuMoCu 13/74/13%	9.9 (.360)	269(39)	181	5.8
CuW-25/75%	14.8 (.538)	228(34)	190	8.3
Aluminum 6061T6	2.75 (.100)	70(10)	170	23.6

Material Properties

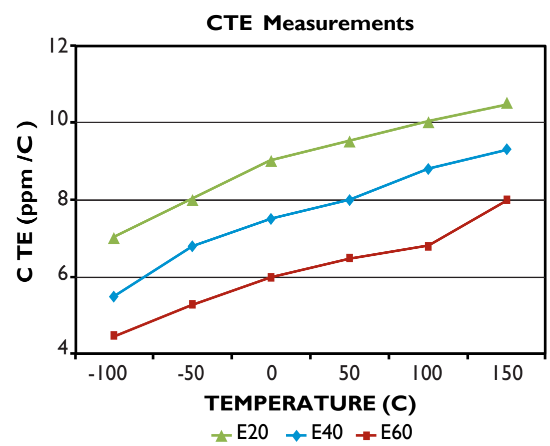
The properties of principal interest to the electronic packaging engineer, designing MCM-L, SEM-E, and RF/Microwave base plates used in the package to dissipate heat and provide a good CTE match to the ceramic package are; a tailorable CTE, high thermal conductivity, high elastic modules to reduce transmissibility, low weight, ease of fabrication using either net shape technologies or conventional machining practices, and- reduced cost.

1.1 Coefficient of Thermal Expansion - The CTE of the three (3) grades of Be-BeO metal matrix composites, E20, E40, E60, have been measured by using a linear dilatometer per ASTM E 228- 85.The data presented in Table 2, represents the averages of a heating and cooling cycle.Ref.2 Additional testing by outside sourcesRef.3; on the E60 composite shows that after thermally cycling 10 times from -55°C to +125°C the CTE averaged, 7.0 ppm/°C, over that temperature range.

CTE Measurements

The materials dimensional stability over a wide range of temperature, see Table 3, is important in electronic packaging applications, especially military avionics, because of the processing temperatures during component assembly, such as gold germanium brazing cycles, plus the duty cycle of the electronic module assemblies. Failure of the substrate material to maintain flatness over temperature, either from a CTE mismatch or dimensional instability during thermal cycling, can lead to premature failure of the solder joint connection of the components to the printed wiring board (PWB) material.

Table 2 – CTE Measurements



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Change in Flatness of E60 after Cryocycling

Cryo-cycling 1.2 Stiffness and Vibration Resistance Analysis. One of the potential failure modes of electronic packages is the dynamic stress exerted on the solder joints by random and sinusoidal vibration experienced in an actual flight environment of military aircraft or in launching of a telecommunications satellite. One way to reduce the effects of this vibration on component life, is to have a core material that has a high elastic modulus, thereby increasing the first mode natural frequency to isolate module from the frequency of its mating hardware and reducing the transmissibility. The benefits of the high specific stiffness of the family of E-Materials (E20, E40, E60) can be seen in the testing that was done at Naval Air Warfare Center.Ref4

Table 3 – Change in Flatness of E60 after Cryo-cycling

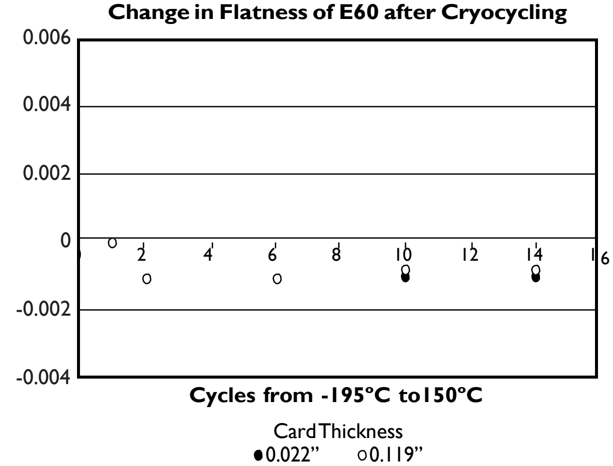
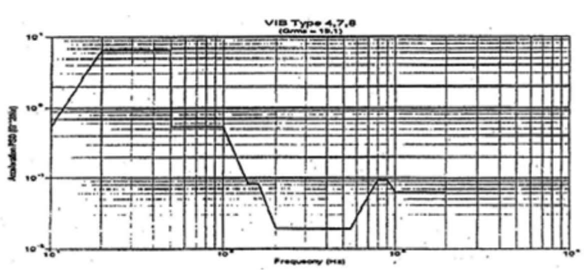


Table 4 – Vibration Testing Results

Material	E-Modulus (MPa)	Natural Frequency (HZ)	G	Transmissibility (Output G/Input G)	Thickness (cm)	Density (g/cc)
AL 6061 T6	68	530	265	8.8	0.250	2.7
AlSiC-70%	255	498	120	4.0	0.245	3.0
BeBeO-E60	330	720	66	1.9	0.241	2.5
BMI/P130 (60%)	280 x axis	630	78	2.6	0.244	1.9
Copper	120	230	525	17.5	0.250	8.2

Table 5 – Vibration F16 MMC Module without Covers – X axis



Another way to look at vibration damage is too look at the cumulative damage ratio (RN) on the solder joints of a .typical line replaceable module (LRM). According to analysis done by Harris for the F22Ref 5, solder joints with lead geometry’s of .0085” wide and .005” high, with a lead stiffness, KD (lb/in) up to 6.82, had 0.01% failure ratio using a BeBeO core bonded to a 0.05” thick Polyimide PWB. This is in comparison to using the same components and PWB with an equal thickness 6061T6 Aluminum core, with a 308.0 ratio. This also assumed a rack transmissibility of 0.3, with the weapons bay open. Texas Instruments Ref 6 also recently tested a E60 core with 8 layer polyimide board bonded on both sides of a 0.100” (2.5mm) thick E60 core with 250 vibratory cycles, 3 axes sequential for 10 minutes per axis, at 6.00 G’s `RMS, for a F16 module on the Modular Mission Computer (MMC) without a solder joint failure on LCCC’s (Leadless Ceramic Chip Carriers) up to 44 IO’s with a 0.050 lead pitch.

1.3 Environmental Testing - With the increasing demands from the package designers, materials not only need to have higher thermal conductivity, tailorable CTE, and a high natural vibration frequency, they must also survive today’s harsh service environments, for them to truly provide total benefit to the end user.

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1.3.1 Salt Fog Testing - E-Materials have been tested for salt fog from 48 hours to up to 500 hours, per MILSTD-810C Method 509-1.Ref.7,both cyclic and static immersion in a 5% NaCl solution, at 95°F. These tests were run on bare E-Materials, a duplex nickel plating, cadmium over nickel, an epoxy primer over chem film, and a conversion coat. All coatings passed 500 hour salt fog testing, except the conversion coat, which survived 96 hours. One testing agency, National Technical Systems. Ref.8, found that if the plating/coating demarcation line is not controlled well in the process that there can be a potential for corrosion to attack the base metal at that point. Therefore, if there is a duplex coating, one of the coatings should overlap the other by 0.005", to prevent preferential attack. They also found that with metal matrix composite materials, the faying surface should have either duplex plating or be anodized to prevent a galvanic cell reaction. This was true for both E Materials and the AlSiC materials that were tested.

Table 6 – Corrosion Test Results Base Material (5% Salt @ 95oF)

Material	Coating	Results	Coating	Results	Coating	Results
6061 T6	Chem Film	Passed 96 hours	Duplex Nickel	Passed 500 hours	Epoxy Primer over Chem Film	Passed 500 hours
E20 BeBeO-E60	Chem Film	Passed 96 hours	Duplex Nickel	Minor damage after 500 hours	Epoxy Primer over Chem Film	Passed 500 hours
E40 BeBeO-E60	Chem Film	Passed 96 hours	Duplex Nickel	Minor damage after 500 hours	Epoxy Primer over Chem Film	Passed 500 hours
AlBeMet®	Chem Film	Passed 96 hours	Chem Film	Minor damage after 500 hours	Epoxy Primer over Chem Film	Passed 500 hours
AlSiC-65%	Chem Film	Passed 96 hours	Duplex Nickel	Passed 500 hours	Epoxy Primer over Chem Film	Passed 500 hours

Case Histories

Satellites - Motorola Satellite Communications Division recently developed for IRIDIUM® a MCM-L packaging design that serves as a transmit/receive module. A large number of packaging design drivers was addressed in the design.ref.9 One of those was the chassis design and material selection. There were four (4) material factors that were evaluated in choosing the right material.

First, due to the high MMIC wattages, a direct physical attachment of the die to a metallic chassis is desired. The chassis' material thermal properties play an important role in maintaining junction temperatures at or below 70oC, thermal conductivity greater than 180 W/mock is needed to provide sufficient thermal conduction.

Secondly, the chassis' materials thermal expansion coefficient (CTE) should be slightly higher than that of the Gas (5.5-5 .7ppm/°C) but within several ppm/°Cutis is important due to both the low fracture toughness of the Gas and the fragility of a .004" finished die thickness. The higher CTE will preferably put the GaAs into a slight compression upon cooling. Also you want the chassis to partially constrain the circuit board material in order to reduce the stress on the copper transmission lines over the temperature cycles. Therefore, a CTE of 8-9 ppm/°C was the targeted range.

The third factor was the chassis' weight, especially on a satellite system where it is not unusual for a launch cost on a per pound basis to be in excess of $10,000/Lb. Therefore the chassis materials weight target was not to exceed 3.1g/cc (0.12lb/in3).

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The fourth factor was the manufacturability/cost of the chassis. The chassis had to be plate able with gold and electroless nickel for wire bonding for ground connections. Further the chassis material had to have good machinability, due to the tight dimensional control of the part dimensions. Also because the design was somewhat immature, there is great benefit to having the flexibility to change dimensions, hole locations, or in general modify the design without having to change expensive net shape tooling. Also the material had to be available in the size needed, 0.550" x 5.5" x 7.5", and in the production time frame.

All of these factors led to Motorola evaluating four materials, AlSiC (50% Vol.), a CuW (75-25%), Sumitomo's A40 (Al-40%Si) material, and the Beryllium/BeO composite E20 (see Table 7).

Table 7 – Materials Selection Chart

Density g/cc	Material	Modulus Gpa(Msi)	Thermal Conductivity @ 25oC-W/m°C	CTE ppm /°C	Plateability Electroless Nickel/Gold	Machinability	Manufacturing Capability Size
14.8	Thermkon 75%W-25%	228 (34)	190	8.3	Good	Good	
3.1	Sumitomo A40	70 (11)	125	13.5	Excellent	Fair	Module size exceeds current mfg capability
3.0	AlSiC 55% Volume SiC	168 (25)	180	9.0	Fair-Results not always predictable	Poor-Need diamond tools or EDM	.125" x 7.5" x 10"
2.06	Brush E20 Be/BeO	303 (44)	215	8.7	Excellent	Good-Can use carbide, EDM, laser	20" x 20" x 20"
8.77	TI-Silvar	110 (16)	153	6.6	Excellent	Good-Can use carbide	1" x 6" x 7"

The advantages of the E20 material in meeting all of the design criteria, low weight, controlled CTE, high thermal conductivity, excellent manufacturability, and a cost that was acceptable within the guidelines and reduced the launch cost, made E20 the material of choice in building the IRIDIUM® chassis (see figure).

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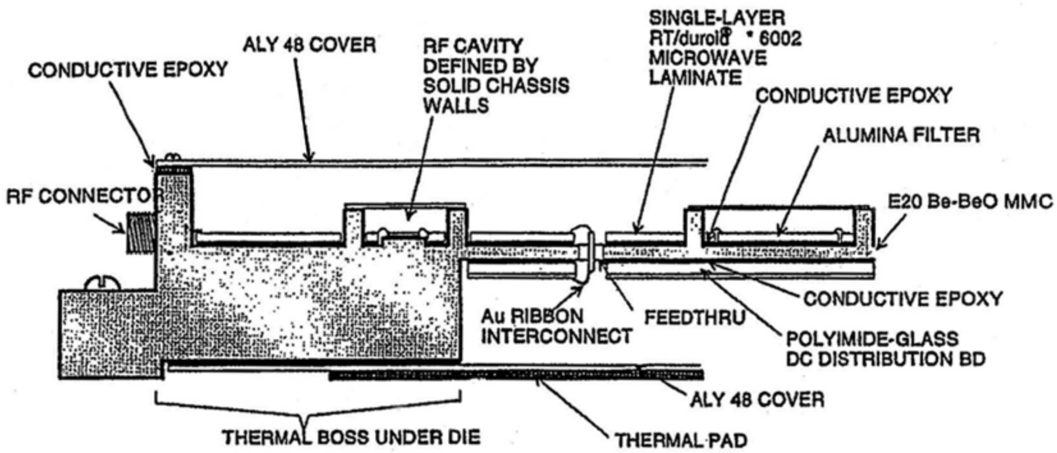
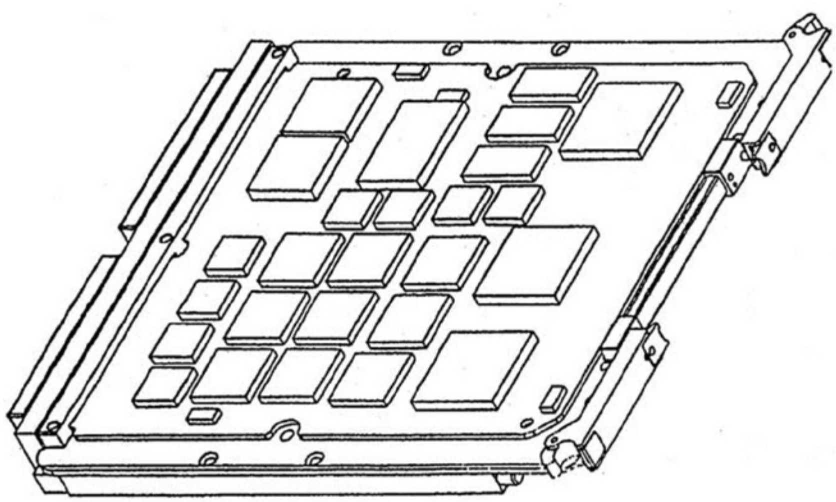
Approach #2 Solid Chassis Walls Define RF Cavities



Aircraft SEM-E Modules – Recent advances in military electronics, Standard Electronic Modules Format E (SEM-E) have created a need for electronic packaging with increased performance and operational lifetimes, while decreasing size and weight. The need for improved thermal management in electronic packaging increased power densities and circuit speeds increase. Enhanced thermal management can improve reliability and, as a results, lower maintenance costs. The SEM-E Heatsinks, Figure 1, is used extensively for thermal management of surface mount designs of military electronics and avionics. In fact on the F22 aircraft, there are reportable over 400 SEM-E modules per aircraft.



SEME-Module: SMT

One of the systems that are currently using SEM-E format module electronics is the F16 Modular Mission Computer (MMC) currently built by Texas Instruments (TI) under contract from Lockheed Fort Worth. TI originally evaluated a number of core (heatsink) materials, CuMoCu, MoGrMO, AlSiC, and E60, for this application. Their design criteria was a matched CTE of the core to the leadless/leaded components in order to provide constrainment of the hard bonded PWB (printed wiring board) to drive the total sandwich CTE down to 8.5-9.5ppm/oC. This required the core material to have a CTE of around 6-7ppm/oC. They also wanted the core material to have a thermal conductivity of at least 180W/m-k in order to provide a good thermal conduction path for cooling the components in order to keep the junction temperatures below 75oC. The remaining design criteria was to reduce the weight of the total module as low as possible, because aircraft avionics as a percentage of the aircraft overall weight is now approaching almost 40% of the total aircraft weight. After a design trade study, TI selected the Be/BeO composite, E60 for their baseline material. REF10

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They then performed a number of qualifying tests on the E60 cores. Among them were vibration testing, random flight and combined sinusoidal-random gunfire vibration. The vibration testing consisted of the following, ESS (Environmental Stress Screen), of 3 axes sequential for 10 minutes per axis, at 6.00G's RMS. They also did thermal cycle testing of the bonded ore, 10 temperature cycles from -54oC to +90oC, for approximately 5 hours per cycle. Each cycle also had a 30 minute dwell time t each temperature extreme. In an independent test apart from the qualification test for MMC, they also tested E60 cores for 960 thermal cycles, 1 hour cycles. After this test, there were no open circuits detected and visual inspection of the E60 cores showed little fatigue of the solder joints. Ref 11 The system is now in production on both the US and NATO F16 upgrades, 350 systems (8 modules per system), with a long range market potential of an additional 300-400 aircraft.

Conclusions

Beryllium based metal matrix composites, E-Materials, have been developed to meet the needs and enhance the performance of advanced electronic packaging applications. The materials have demonstrated in test and production, for both aircraft and satellite applications, that they can meet the avionic packaging designers' needs for a high modulus, high thermal conductivity, low density, and tailorable coefficient of thermal expansion material. At the same time, they can provide a cost-effective solution to the system's needs for improved reliability, lower life cycle costs, and reduced weight.

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Bibliography

Thomas Parsonage received a B.A. degree in Marketing from Michigan State University in 1996. He joined Materion Beryllium & Composites, Inc. in 1967. He was the Director of Market Development for the Beryllium Products Group at Materion Beryllium & Composites before his retirement in 2009. During his tenure, he was involved in application development in all aspects of the electronic packaging market and has authored three papers involving the development and use of beryllium composites for advanced electronic packaging applications. For info on Materion Beryllium products contact 419.862.4173.

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