Use of Aluminum-Beryllium Composites for Advanced Avionics Systems

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ABSTRACT

Avionics requirements for aircraft and satellite systems continue to increase, requiring higher packaging densities, lower delta junction temperatures, higher heat loads, smaller and lighter packaging utilizing chip on board, BGA and surface mount technologies that continue to challenge materials development. To address these increased performance needs, Materion Beryllium & Composites has developed a family of new metal matrix materials, AlBeMet® and E-Materials, for these increased performance avionics systems. This paper will describe the general material attributes of AlBeMet and E-Materials first, and then look at the application of these properties in the design and packaging of advanced avionics electronic products.

These materials offer the design engineer a combination of light weight, high thermal conductivity, and tailorable coefficient of thermal expansion (CTE), high specific stiffness and thermal stability, with mechanical properties that have a high degree of isotropy. These materials are manufactured by conventional powder metallurgy technology, while at the same time being able to be fabricated with conventional aluminum technology.

Keywords: Metal Matrix Composites, Aluminum-Beryllium, AlBeMet, E-Materials, Avionics Systems

INTRODUCTION

AlBeMet® is a family of metal matrix composite made up principally of beryllium and aluminum. We can vary the ratio of the two metals to alter the physical, thermal and mechanical properties. The first composition offered to the market is AlBeMet® 162, a 62% Beryllium/38% Aluminum composite. This material is a powder metallurgy product produced by gas atomization, and the final product forms, rod, bar, tube, sheet are derived by consolidating the aluminum/beryllium powder by Hot Isostatic Pressing (HIP) and Cold Isostatic Pressing (CIP) followed by extrusion or sheet rolling processes.

Avionics systems require reduction in weight, while needing to increase the first mode frequency (deflection) of the system to decouple the avionics suite from the systems frequencies, in order to minimize the stress from vibration on the leads, solder joints and substrates, and to increase the fatigue life of the electronic packages. AlBeMet® 162 with a density of 2.1 g/cc (0.076 Lb/in-3), combined with an elastic modulus of 180 GPa (28 Msi), provides a unique combination of physical properties and specific stiffness (E/ρ) that is 4 X aluminum, to address those needs (Table 1).

Table 1 – Physical Properties of AlBeMet® AM162 Wrought compared to Common Aluminum

Property	2024T6	6061T6	AM162H
Density g/cc (Lbs/in^3)	2.77 (0.100)	2.70 (0.100)	2.10 (0.076)
Modulus GPa (Msi)	72 (10.5)	69 (10.0)	193 (28)
Poisson's Ratio		0.23	0.17
Coefficient of Thermal Expansion @ 25C ppm/C	22.9 (12.7)	23.6 (13.1)	13.9 (7.7)
Thermal Conductivity, W/m	151	180	210
Specific Heat @ 20C J/kg°K	875	896	1506
Electrical Conductivity %IACS	38	43	49
Damping Capacity @ 25C & 500Hz	1.05×10^{-2}	1.05×10^{-2}	1.05×10^{-3}
Fracture Toughness K1C2 Ksi√in	23 (T-L)	23 (T-L)	10-21 (T-L)

The mechanical properties of AM162 have been extensively characterized in all three product forms, but a significant design data base has been developed for the extruded product form. The extruded bar is fabricated by CIPing the isotropic spherical aluminum-beryllium powder into semi-dense billets and then canning the billet for subsequent extrusion with a minimum of a 4:1 reduction ratio. The room temperature tensile properties are given in Table 2.

Table 2 - Typical Room Temperature Tensile Properties of AM162

Product	Heat Treatment	Yield Strength MPa (Ksi)	Ultimate Strength MPa (Ksi)	Elongation %
HIP	593°C/24 hours	221 (32)	288 (42)	4
Extruded (L)	593°C/24 hours	328 (47)	439 (63)	9
Sheet (L)	593°C/24 hours	314 (45)	413 (60)	7

The room temperature tensile strength of the wrought forms of AM 162 compares favorably to 6061T6 Aluminum, and are less than the 2024T6 Aluminum. There is no observable notch brittleness in AM 162 extruded material. The strength ratios for all conditions were greater than 1, with stress concentration factor of Kt 3. The sharp notch strength to yield-strength ratio (NRS) values were higher in the longitudinal direction compared to the longitudinal-transverse direction. Also the NRS tended to increase slightly at elevated temperatures indicating plastic flow (Table 3). There was no indication of hole tearing or breakout in the holes during bolt bearing testing.

Table 3 - Notch/Pin Bearing Strength Data AM162 Extruded

Test Conditions	Notch Strength (MPa (Ksi)	NSR	Bearing Strain %	Bearing Stress MPa (Ksi)
195°C L 195°C T	556 (80.8) 482 (70.0)	1.5 1.3		NT
21°C L 21°C T	513 (74.4) 435 (63.1)	1.6 1.3	8.9 6.4	349 (50.6) L 333 (48.3) T
200°C L 200°C T	641 (50.3) 344 (50.0)	1.6 1.3		NT

The fatigue properties of AlBeMet® extruded material have been tested using the Krause rotating beam fatigue test utilizing fully reversed cycles with an R+0.1. The fatigue limit, 1 X 10-7 cycles was about 207 MPa (30 Ksi) in the longitudinal direction and 165 MPa (24 Ksi) in the transverse direction. This property is approximately 75% of the minimum RT yield strength, which is 2 X that of typical fatigue properties of 6061T6 aluminum. This is important for applications where cyclic fatigue is critical to the life cycle of the component.

AlBeMet® 162 sheet and extruded products have been tested for stress corrosion by Materion Beryllium & Composites and independent laboratories including the European Space Agency (ESTEC) materials lab. The testing consisted of using the ASTM G38-73 test procedure, C-ring Stress Corrosion Testing, and subjecting the specimens to 30 days in a 3.5% sodium chloride (NaCl) solution. The results indicate that none of the specimens failed during the 30 days testing, and in subsequent tensile strength testing no degradation. ESTEC/ESA have given their approval for the use of AlBeMet® 162 and 150 grades for use on satellite structures for European Spacecraft.

In terms of fabricating technologies, AlBeMet® materials can be conventionally machined using carbide cutters, at speeds and feeds that are approximately 15–20% slower than machining 6061T6 aluminum. The significant difference is increased tool wear due to the abrasive nature of the beryllium portion of the matrix, typically 2 X that of aluminum. Forming the sheet material is similar to aluminum, in that the same tooling and temperature ranges can usually be applied, but at a higher forming temperature, typically over 200°C (400°F). The forming rate is slightly slower for AlBeMet® materials. Like aluminum AlBeMet® materials can be coated with typical aluminum protective coatings from ChemFilm (Alodine) to Cadmium over Nickel, depending on service environment. Current applications have passed 500 salt fog test using methods including anodizing (Class 1 Type 1); electroless nickel plating and cadmium plating over nickel.

AlBeMet® materials can be joined utilizing many of the same joining technologies for aluminum. The material can be vacuum and dip brazed, electron beam welded, TIG welded and there is currently work being done on laser welding technologies. Table 5 indicates the typical values obtained utilizing these processes based on limited test data.

Table 5 – Joining

AlBeMet® AM162	Typical Joint Strengths
Epoxy Bonding – Phenolic Epoxy Primer	4,000 psi (Shear)
Hysol High Strength Epoxy	
Dip Brazing, 580°C, Braze Alloy 718	14,500 Psi (Shear)
Fluxless Vacuum Brazing	10,000 Psi (Tensile)
Tig Welding	30,000 Psi (Tensile)
EB Welding	42,000 Psi (Tensile)

E-Materials is a family of metal matrix composites made up principally of beryllium and single crystal beryllium oxide platelets. We can vary the volume % ratio of the two materials to alter the physical, thermal and mechanical properties. Materion Beryllium & Composites currently offers 3 grades: E20, E40 and E60. These materials are produced by blending beryllium and beryllium oxide powders into a homogeneous mixture to ensure isotropy of physical and thermal properties. These powders are then Hot Isostatically Pressed (HIP) into fully dense blocks for further processing to yield finished blanks for subsequent machining into components.

The properties of principle interest to the electronic packaging engineer designing heat sinks for MCM-L, SEM-E, BGA and RF-Microwave applications are: a tailorable CTE, high thermal conductivity, high elastic modulus to reduce transmissibility to the components and low weight (table 6).

Table 6. Typical Properties of Electronic Packaging Materials

Material	Density (g/cc)	Modulus (GPa)	Thermal Conductivity (W/m-k)	CTE ppm/°C
E20	2.06	303	210	8.7
E40	2.3	317	220	7.5
E60	2.52	330	230	6.1
AlSiC (70%)	3.01	220	170	6.7
Kovar	8.1	140	14	5.9
CuMoCu	9.9	269	181	5.8
CuW (25%/75%)	14.8	228	190	8.3

The CTE is a critical property in packaging electronics, as mismatched materials will tend to cause premature fatigue in component attachments. The CTE of all 3 E-Materials have been measured by using a linear dilatometer per ASTM E 228-85 over temperature ranges of -100°C to +450°C. All 3 grades have a uniform slope to the change in CTE as a function of temperature change. They also match, over AuSn and AuGe brazing/soldering temperatures, conventional ring frame materials like Kovar, Alloy 46 or 48, that are used in hermetic packaging applications.

One of the potential failure modes of the electronic components is the dynamic stresses exerted on the solder or adhesive bonded joints of the package devices, by either random or sinusoidal vibration experienced in an actual flight or launch environment. One way to reduce the effects of this vibration on component life is to have a heatsink/thermal plane material with a high elastic modulus, thereby increasing the first mode natural frequency of the package to isolate it from the frequency of its mating hardware. The elastic modulus of the E-Materials ranges from 310 GPA to 331 GPA. This combined with the low weight of these materials provides a very high specific stiffness that has a positive effect on the transmissibility of vibration to the package and improves solder fatigue life of the solder joints.

E-Materials with no coatings will corrode similar to 6061T6 aluminum in a 3.5% NaCl salt solution, approximately 0.02 mg/cm-cm/day. Coatings can be applied similar to aluminum (as was previously discussed for AlBeMet® such as ChemFilm, electroless nickel, chrome, cadmium over nickel, etc.).

Specifically addressing the design of avionics for the military, the packaging task is made much more difficult by both the extreme environment that the electronics will be subjected to, and the typically state of the art components that will populate the Printed Wiring Assembly (PWA). When dealing with large pin out Surface Mount Technology (SMT) devices, particularly in the case of Leadless Chip Carriers (LCC), the Printed Wiring Board (PWB) material and associated heatsink material must be carefully selected to minimize solder joint fatigue over the expected lifetime of temperature cycles. In addition, the overall dimensions of a PWA may also complicate the selection of PWB and Heatsink materials, as flexure of the assembly will become a factor as at least one of the X - Y dimensions become large. Another compelling factor in avionics packaging is weight. Weight is a critical parameter for military aircraft performance, and increased cost will often be accepted in order to achieve reduced weight.

Before jumping into the discussion of avionics packaging, it is useful to examine the common practices utilized in common commercial applications. Most commercial electronics are designed with PWBs made of FR-4, GR-4, Polyimide or other low cost materials. Heat sinks (cores), if required, are generally made from aluminum, due to its low cost and ease of machining. These practices work well for electronics that are typically used in office, lab or factory environments. There are no requirements for survival of rigorous temperature cycling or random vibration testing to qualify the hardware for deployment in the military environment. Without the increased operating temperature range, typically -40 degrees Celsius to +150 degrees Celsius, the PWB and Heatsink material perform adequately. If subjected to such temperature cycling, Avionics Integrity analysis shows that movement of the PWB material in the X - Y direction quickly fatigues the solder joints on the PWA. Additional analysis shows that large commercial PWAs (one or both dimensions larger than 6 inches) begin to flex under the typical military program random vibration profiles, to an extent that damages solder joints. Clearly the designs that serve the commercial world so well require a ruggedized packaging for the military avionics environment.

In packaging electronics for the Avionics environment, the selection of the PWB material and core material are critical decisions. Although not the subject of this paper, much thought must go into selecting PWB material, as it must display properties independent of the core material, as well as those characteristics that must work in concert with the core. A major consideration is the CTE match between PWB material and components, most critically the LCCs and leadless resistors and capacitors, as any significant mismatch tends to over stress the solder joints. Epoxy Glass and Epoxy Paper PWB materials have CTEs in the range of 11 - 16 (PPM/degree C). The CTEs for the ceramics range from 5 - 7 (PPM/degree C).

After much consideration at Lockheed-Martin Electronics and Missiles, the majority of PWB designs utilize Cynate-ester or Kevlar (both woven and non-woven forms of Kevlar materials are used). The Kevlar boards, although more expensive than Epoxy Glass or Polyimide Glass, display a CTE similar to ceramics in the 6 - 7 PPM/degree C. In applying an integrity/durability analysis to a woven Kevlar PWB bonded to an Aluminum core, it was determined that subjected to typical thermal cycling requirements, the thermal mismatch of the materials would cause solder joint fatigue and failure prior to typical durability life requirements. Specifically, for LCC components with greater than 44 pin outs, the movement of the PWB prematurely fatigues the solder joints. Smaller LCC devices and leaded SMT devices perform better, but do not perform sufficiently for a durability lifetime requirement of 20 years. The performance can be improved by increasing the thickness of the aluminum core and/or using a hard bond (PWB to Core) approach. An unacceptable increase in weight is the result of the increase in aluminum core thickness, while hard bonding of PWB to Core does not provide the required increase in durability.

To improve this baseline performance, a core material needs to be selected that better matches the CTE of Kevlar. For many years a reasonable solution was to use an AlSiC heatsink. The AlSiC material has a CTE of 16.2 compared to that of 23.6 for Aluminum. The downside associated with AlSiC however, tended to outweigh the benefits. Specifically, AlSiC can be up to two orders of magnitude more expensive than Aluminum, does not have as good thermal conductivity, and is virtually impossible to machine in terms of including features in the Z-Axis, or to allow for cutouts in the material. An improvement to the AlSiC solution is Beryllium-Beryllium Oxide (BeBeO). BeBeO will outperform the AlSiC for larger PWA applications, offering a much stiffer material. In addition, the thermal conductivity is better and the material offers an improvement over AlSiC in terms of machining. The cost is still comparatively high, similar to AlSiC, and although easier to machine than AlSiC, it is still less attractive in terms of machinability and cost than other alternatives.

For the best solution to yield the highest durability in PWAs, Aluminum Beryllium (AlBe) becomes the material of choice. The CTE of 13.9 PPM/degree Celsius is a marked improvement from the AlSiC material, and has a much improved thermal conductivity. Perhaps the best advantage is the ability to machine the AlBe almost as easily as Aluminum (such as 6061 T6). Fabricating and performing durability life testing on a non-woven Kevlar PWB bonded to a AlBe core (brazed liquid flow through construction) with PWBs bonded to both sides of the core with components including leaded SMT devices of 25 mil pitch and 20 mil pitch, LCCs up to 68 I/O, 68 I/O J-lead devices, 84 I/O leaded SMT packages, 2" X 2" and 2" X 4" 25 mil pitch MCMs and a 25 mil pitch edge connector yielded test data demonstrating a life clearly in excess of 20 years, the current Air force bench mark for Avionics.

The first solder joint to fail did so at 1223 thermal cycles (-40 to +85 degrees C), and the testing continued to 6000 cycles with a total of 5 failed solder joints (failures occurring on cycle numbers 1499, 4837, 4909 and 4943) on the first unit, all on 68 pin LCC devices. There were 6 failures on the second unit, at cycle numbers 1066, 2427, 3786, 3897, 4060 and 5258. The vibration results were equally impressive with no failures in solder joints detected in the 120 minutes at 7.703 g RMS (simulating the 20 year life). The test unit increased the level to 9.16 g RMS for 30 minutes, 10.894 g RMS for 30 minutes, 12,955 g RMS for 30 minutes and finally 15.406 g RMS for 60 minutes before detecting an intermittent solder joint. Clearly with the AlBe core better CTE matched to the Kevlar PWB, and serving to constrain the PWB movement, the effect is a more rigid assembly that performs well in both vibration and thermal environments far in excess of military requirements.

As the size of a module grows, with one or both dimensions exceeding six inches, the effects of vibration causing flexing of the assembly must be taken into account. In designs based on Aluminum cores the flexure causes premature solder joint failures. The AlBe core design in contrast, offers a much greater rigidity and facilitates the module tolerating higher vibration levels over greater periods of time (as evidenced by the above referenced data).

This performance improvement can be attributed to the characteristics of AlBe over Aluminum. Specifically the difference in Modulus accounts for the improved performance with AlBe having a modulus of 193 GPA versus Aluminum with a modulus of 69 GPA. In terms of flexibility of design, this property enables the designer to create thinner cores that will allow modules with specific envelopes such as a SEM-E module to be thin enough to fit in the allocated standard rack slot of 0.6 inches, while giving sufficient heights to components on PWBs on both sides of the core.

The last major concern in selecting cores for electronic modules is the weight. Where an Aluminum module can be made to survive a harsh environment by increasing the thickness of the core, the penalty is weight. In a SEM-E module for example with a maximum weight allowed of 1.5 lbs., and a maximum module thickness dimension of .6 inches, the approach of increasing the aluminum thickness is not a feasible solution. By taking this approach both weight and thickness specifications are violated. The far superior solution is the AlBe core. An AlBe core will offer a 28% lower weight for a similar volume Aluminum core, and will fit into a smaller volume to provide a greater stiffness.

A thinner core can provide the stiffness that a thicker Aluminum core would provide, meet the weight requirements, and fit into the maximum module thickness. Machined AlBe covers for EMI shielding also offer weight savings over the Aluminum counterpart. The weight savings are not constrained to electronic modules. Castable AlBe materials offer alternatives for any aluminum structure that is cast, or wrought material for those structures that are machined, while providing the 28% weight saving. Additional weight savings can be realized as the improved modulus property of AlBe is exploited, and structures can be re-designed from their Aluminum form to be re-invented with less total material volume.

CONCLUSION

In summary, Avionics electronics design faces the challenges of minimizing solder joint fatigue, achieving a useful life in excess of 20 years, dealing with the effects of large Printed Wiring Assemblies' flexure and meeting challenging weight targets. The careful incorporation of AlBe into those designs can aid in achieving those design goals to produce durable Avionics that meet the extreme environments imposed upon them.

Note:
Handling Aluminum-Beryllium materials in solid form poses no special health risk. Like many industrial materials, beryllium-containing materials may pose a health risk if recommended safe handling practices are not followed. Inhalation of airborne beryllium may cause a serious lung disorder in susceptible individuals. The Occupational Safety and Health Administration (OSHA) has set mandatory limits on occupational respiratory exposures. Read and follow the guidance in the Material Safety Data Sheet (MSDS) before working with this material. For additional information on safe handling practices or technical data on Aluminum Beryllium materials, contact Materion Beryllium & Composites.

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