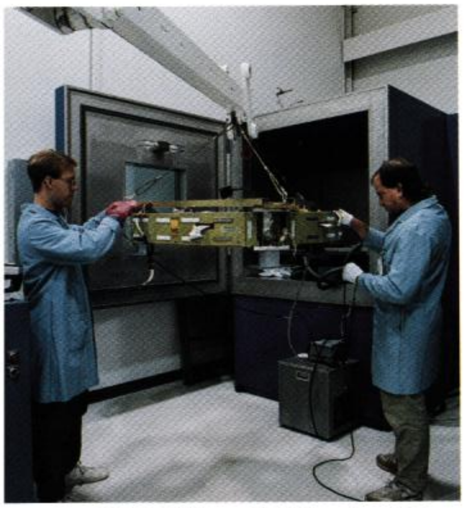
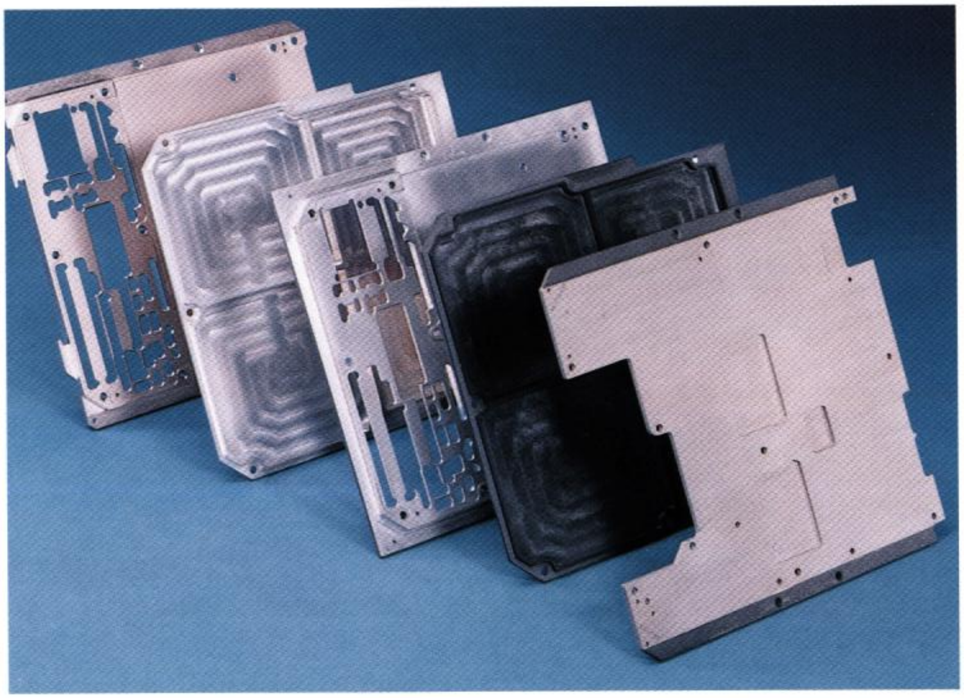
Beryllium Metal Matrix Composite
Avionics Materials

Introduction

Requirements for aircraft and satellite avionic systems continue to challenge materials development. Designers are seeking higher packaging densities, lower delta junction temperatures, higher heat loads, smaller and lighter packaging utilizing chip on board, BGA, and more advanced surface mount technologies. To address these higher performance needs, Brush Wellman, Inc. has developed a family of new metal matrix materials, AlBeMet® and E Materials. These materials offer the design engineer a combination of light weight, high thermal conductivity, tailorable coefficient of thermal expansion, high specific stiffness, thermal stability and mechanical properties with a high degree of isotropy. Both materials are manufactured using conventional powder metallurgy technology and therefore can be fabricated with conventional metalworking technology.



ORBCOMM® satellite being placed into a chamber for thermal cycle testing



AlBeMet® SEM-E heat sinks and covers

Cover Photos: Top, Comanche Helicopter, courtesy of Boeing Sikorsky; Middle, Global Star Satellite, courtesy of Space Systems/Loral; Bottom, F-22 Fighter, courtesy of Lockheed Martin.

AlBeMet®

This is a family of metal matrix composites made up principally of beryllium and aluminum. The ratio of the two metals can be varied to achieve the desired physical, thermal and mechanical properties.

One composition, **AlBeMet® (AM 162)**, is a 62% beryllium/38% aluminum composite. This is a powder metallurgy product produced by gas atomization and is available in the form of rod, bar, tube and sheet. These shapes 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. The material is also available as an investment casting under the name **AlBeCast™**.

Physical Properties

High performance avionic systems require reductions in weight with increases in the first mode frequency (deflection) to decouple the avionic suite from the system frequencies. This is necessary to minimize the stress from vibration on the leads, solder joints and substrates and to increase the fatigue life of the electronic packages. **AlBeMet®** with a density of 2.1g/cc (0.076Lb/in^3), combined with an elastic modulus of 193 Gpa (28Msi), provides a unique combination of physical properties, particularly stiffness (E/p) that is four times that of aluminum to address these high performance needs (Table 1).

Mechanical Properties

Tensile Strength

The mechanical properties of **AlBeMet®** have been extensively characterized in all four product forms, but a significant design data base has been developed for the extruded product form (Table 2).

The extruded bar is fabricated by CIP'ing 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. Tensile testing was conducted using tapered-end specimens with a 0.25″ (0.635cm) diameter gauge in both the longitudinal and long-transverse directions. Testing was performed using ASTM-E8 guidelines. The room temperature typical tensile properties are given in Table 2. The room temperature tensile strength of the wrought forms of **AM 162** compare favorably to 6061T6 aluminum, and are less than 2024T6 aluminum. This property was important to the ORBCOMM® satellite, where high loads resulting from the Pegasus launch transient meant that a high strength material was needed for the spacecraft construction, equal to or better than 6061T6 aluminum.

The spacecraft structure also needed ductility in order to accommodate the shock loads at the interface of the non-explosive separation bolts of the spacecraft and the release of the pre-load energy on the bolts. Like many metals, the tensile properties increase with decreasing temperature and decrease with increasing temperature.

Table 1

Comparison Properties of Selected Aluminum Grades and AlBeMet® AM 162 Wrought

Property	2024T6	6061T6	AM 162
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	0.23	0.17
Coefficient of Thermal Expansion @25C ppm/C(ppm/F)	22.9 (12.7)	23.6 (13.1)	13.9 (7.7)
Thermal Conductivity, W/mk	151	180	210
Specific Heat @ 20C J/kg°K	875	896	1506
Electrical Conductivity % IACS	38	43	49
Damping Capacity @25C and 500 HZ	1.05×10^{-2}	1.05×10^{-2}	1.5×10^{-3}
Fracture Toughness K_{IC} KSI$\sqrt{IN}$	23 (T-L)	23 (T-L)	10-21 (T-L)

Table 2

Typical Room Temperature Tensile Properties AM 162

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

Notched Strength/Pin Bearing Strength

There is no observable notch brittleness in **AM 162** extruded material. The strength ratios for all conditions were greater than 1, with a 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. Based on old Lockalloy data, NRS ratios of 0.98, there may be some notch sensitivity in the **AM 162** sheet material; this will be tested in the future. The notch strengthening indicated in the **AM 162** extruded material was of significant design value to the ORBCOMM® satellite. Shock loading of the spacecraft is accomplished by simultaneously releasing three separation bolts that connect the spacecraft to each other. While the release is non-explosive, the shock levels are high due to the stored energy in the preloaded bolts. Even after repeated separation tests, no cracks were observed in the separation brackets or vertical gussets that were made from **AM 162** material.

Table 3

Notch/Pin Bearing Strength Data AM 162 Extruded

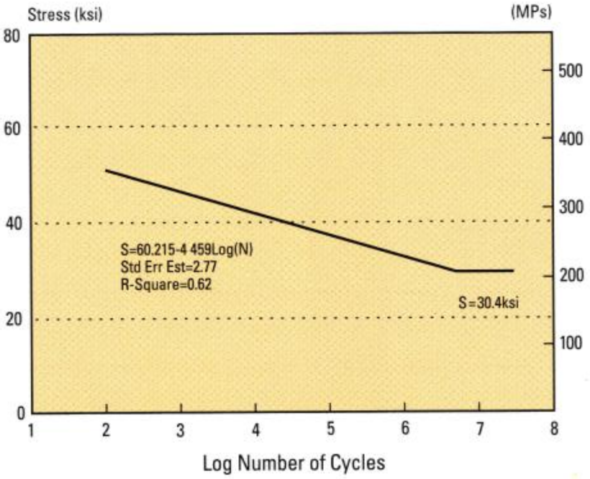
Test Conditions	Notch Strength Mpa (Ksi)	NSR	Bearing Strain %	Bearing Stress Mpa (Ksi)
−195°C L	556 (80.8)	1.5		Not Tested
T	482 (70.0)	1.3		
21°C L	513 (74.4)	1.6	8.9	349 (50.6)L
T	435 (63.1)	1.3	6.4	333 (48.3)T
200°C L	344 (50.3)	1.6		Not Tested
T	344 (50.0)	1.3		

Fatigue Properties

The fatigue properties of **AlBeMet®** extruded material, Figure 1, have been tested using the Krause rotating beam fatigue test utilizing fully reversed cycles with a R=-1. The fatigue limit, 1 x 10^{-8} cycles, was about 207 Mpa (30Ksi) in the transverse direction. This property is approximately 75% of the minimum RT yield strength, which is 2X that of typical fatigue properties for 6061T6 aluminum. This is important for applications where cyclic fatigue is critical to the life of the component.

Figure 1

Rotating Beam Fatigue Longitudinal AlBeMet® 162



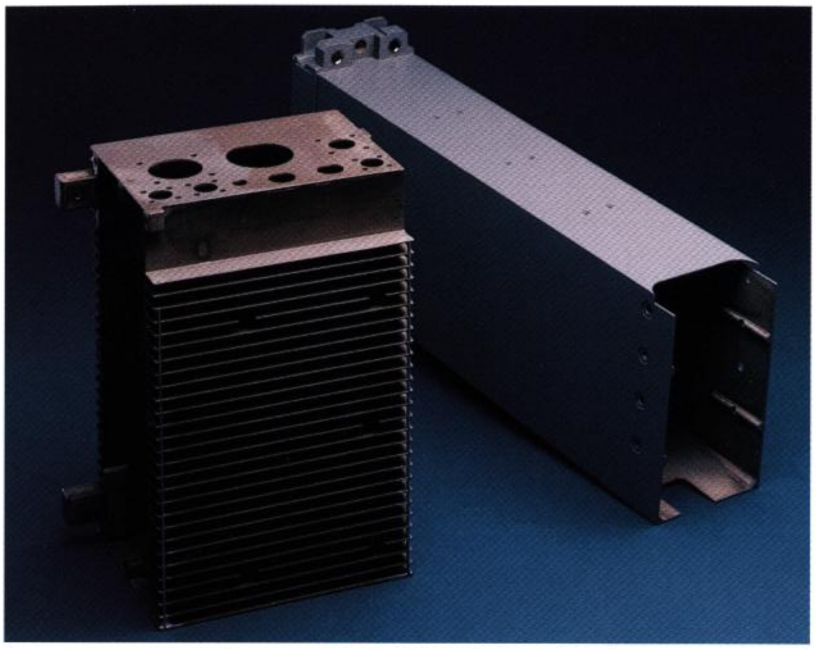
Stress Corrosion Cracking

AlBeMet® 162 sheet and extruded products have been tested for stress corrosion cracking by Brush Wellman and independent laboratories like the European Space Agency (ESTEC) materials laboratory.

Both tests demonstrated that **AM 162** sheet and extrusions are not susceptible to stress corrosion cracking. The testing at Brush Wellman 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 C-Ring specimens were taken from four orientations in multiple extrusion lots; transverse longitudinal (TL), longitudinal transverse (LT), longitudinal short transverse (LS), and short transverse (ST). The rings were then loaded under a constant strain.

AlBeMet® vacuum brazed liquid flow through module

Dip brazed AlBeMet® chassis



The testing at ESTEC used ASTM E8-m subsize specimens which were subjected to 75% of the 0.2% proof stress (yield strength) and immersed in 3.5% NaCl solution for 10 minutes and dried for 50 minutes. This procedure, repeated over a 30 day period, was done to both sheet and extruded material. The results, seen in Table 4, indicate that none of the specimens failed during the 30 days testing and in subsequent tensile testing no degradation (there was even a slight increase in mechanical strength) was observed.

Table 4

ESTEC Stress Corrosion Cracking Test Results

Specimen	Stress during SCC test (Mpa)	Rp0.2 Mpa (Yield)	R_m (UTS)	Elongation % after fracture	E Gpa	Time to Failure Hours
AM 150 RL	244.5	356.8	398.6	1.3	167.3	(There were no failures)
AM 150 RT	244.5	344.4	391.5	2.23	176.2	
AVG.	244.5	350.6	395.1	1.77	171.8	
AM 162 RL	291	411	425.1	1.0	198.0	
AM 162 RT	291	403	408.1	1.0	244.6	
AVG.	291	407	416.6	1.0	221.3	

ESTEC/ESA has given its approval for the use of **AM 162** and another grade, **AlBeMet® AM 150** for use on satellite structures for European spacecraft.

Fabrication Technologies

Machining

Fabricating **AlBeMet®** materials is very similar to fabricating aluminum. The material 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 over aluminum due to the abrasive nature of the beryllium portion of the matrix, typically two times that of aluminum. Forming of the sheet material is similar to aluminum, in that the same tooling and temperature ranges can usually be used, but at a higher forming temperature – typically over 200°C (400°F). The forming rate is slightly slower for **AlBeMet®** materials, especially if severe bending is required. For the ORBCOMM® satellite, the forming of the **AM 150** sheet material was done at the same rate as an aluminum panel. The principal fabrication difference between **AlBeMet®** and aluminum is the need for a facility that can handle beryllium containing materials to remove the fine, airborne particles that could pose a health risk in individuals that are sensitive to the material. Contact Brush Wellman for further information on safe handling of beryllium containing materials.

Coating

Like aluminum, **AlBeMet®** materials can be coated with typical aluminum protective coatings from Chemfilm (Alodine) to Cadmium over nickel, depending on the service environment. One application for electronic modules required the **AlBeMet®** to pass a 500 hour salt fog test. That has been successfully accomplished by either anodizing (Class 1, Type 1) electroless nickel plating or cadmium plating over nickel. Another coating that provides not only corrosion protection but is also useful for adhesive bonding of structures is BR 127, a sprayed on adhesive primer, that was used for the ORBCOMM® honeycomb panels. Using this coating allows the coated parts to be stored for months, if necessary, prior to final assembly. After storage, the primed surface only needs to be wiped with an alcohol solution to prepare it for active bonding. This coating also eliminates the need for the final user to do anything to the **AlBeMet®** bare surface prior to bonding.

Joining Technologies

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

Table 5

Typical Joint Strengths for AlBeMet® 162

Epoxy Bonding BR 127Primer plus Hysol High Strength Epoxy	4,000 Psi (Shear) (27 Mpa)
Dip Brazing, 580°C, Braze Alloy 718	14,500 Psi (Shear) (98 Mpa)
Fluxless Vacuum Brazing	10,000 Psi (Tensile) (68 Mpa)
TIG Welding	30,000 Psi (Tensile) (203 Mpa)
EB Welding	42,000 Psi (Tensile) (285 Mpa)

Joints for **AlBeMet®** materials must be designed differently than those for aluminum. Aluminum usually fails in a ductile manner, so bending occurs before failure and usually occurs in the joint. With **AlBeMet®** materials, the metal is stiffer, so the joint must be designed so the parent metal breaks before the joint fails. In this fail-safe design, the joints are not the weak link in the design and therefore will take the stress build-up without failure.

E Materials

This is a family of metal matrix composites made up principally of beryllium and crystal beryllium oxide platelets. Brush Wellman varies the volume percentage ratio of the two materials to tailor the specific physical, thermal, and mechanical properties required. Currently, three grades of **E Materials** are offered – **E20**, **E40**, **E60**. These materials are produced by blending the beryllium and beryllium oxide powders into a homogeneous mixture to create isotropy of physical and thermal properties. This mix is then hot isostatically pressed (HIP) into fully dense blocks for further processing into finished blanks and subsequent machining into components.

Physical Properties

The properties of principal interest to designers of electronic packaging heatsinks for MCM-L, SEM-E, BGA's and RF/Microwave applications are a tailorable coefficient of thermal expansion (CTE), high thermal conductivity, high elastic modulus to reduce transmissibility to the components, and low weight (Table 6).

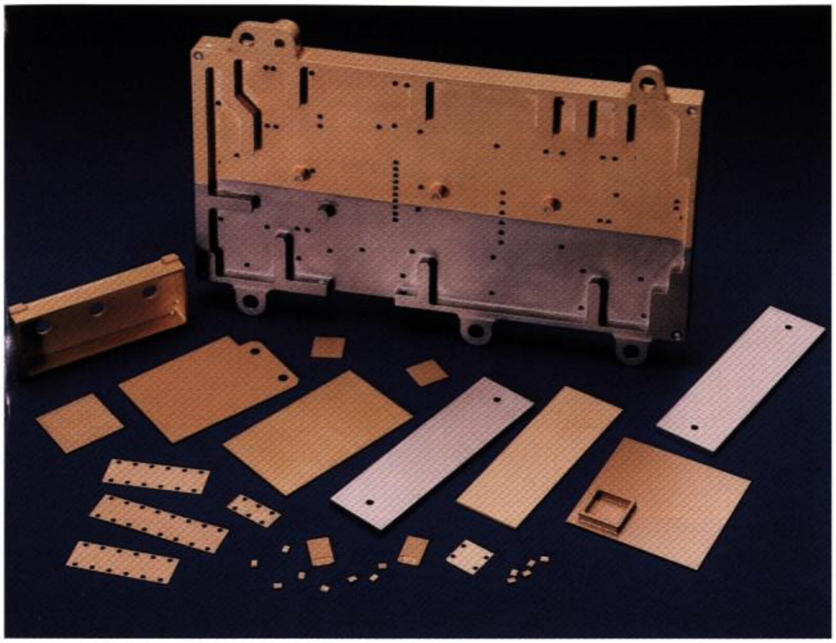
Table 6

Materials for Electronic Packaging Typical Properties

Material	Density g/cc	Modulus Gpa	Thermal Conductivity W/m-k	CTE ppm/°C avg.25-50°C
E20	2.06	303	210	8.7
E40	2.30	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 13/74/13	9.9	269	181	5.8
CuW-25/75%	14.8	228	190	8.3

Thermal Properties

The coefficient of thermal expansion (CTE) is an important property in electronic packaging applications. It is a requirement for helping constrain printed wiring boards (PWB's) in avionic SEM-E type modules that use surface mount devices that are leadless chip carriers. It is also useful for matching the CTE of die materials like GaAs or Silicon in RF/Microwave type applications.

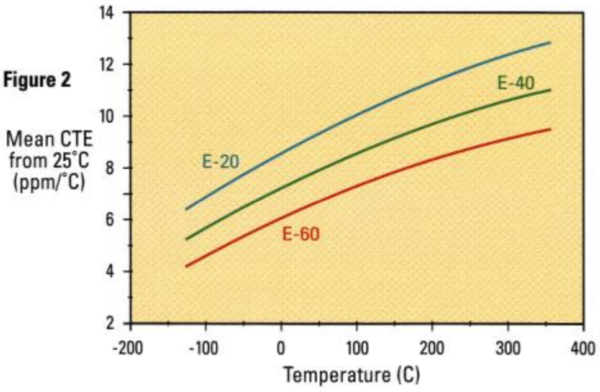


E Material bases and carriers for hermetic packages. Plating is either gold or silver.

The CTE of all three grades of **E Materials** have been measured by using a linear dilatometer per ASTM E228-85 over temperature ranges from -100°C to +450°C (Figure 2). All three grades, **E20**, **E40**, **E60**, 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.

The remaining thermal properties, specific heat and thermal conductivity, have been measured for all three grades of **E Materials**. The specific heat of the composites vary as a function of volume loading of the matrix. **E20** has a specific heat of 1.584 J/gK; **E40** - 1.41 J/gK; **E60** - 1.26 J/gK. In comparison, 15% Cu/85%W has a specific heat of 0.171 J/gK or approximately 15% of the E Materials. The thermal conductivity of the three **E Materials** grades has been measured over a temperature range from -100°C to +150°C.

Figure 2



E Material SEM-E cores and thermal planes with nickel, cadmium and BR 127 plating.

In general the thermal conductivity has an inverse relationship to temperature (decreases with increasing temperature and increases with decreasing temperatures).

Stiffness/Vibration Resistance

One of the potential failure modes of the electronic components is the result of dynamic stresses exerted on the solder or adhesive bonded joints of the package devices. This is caused 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** (**E20**, **E40**, **E60**) ranges from 310 Gpa (44Msi) to 331 Gpa (48Msi). 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 of the package and improves the solder fatigue life of the solder joints. This was demonstrated in tests at the Naval Air Warfare Center (See Table 7). The **E60** material also had 1/5th the displacement (amplitude) of the AlSiC (65% loaded SiC). Testing at a major avionics producer indicated that for equal vibration frequency, **E60** would require 1/3 less the section thickness than CuMoCu or CuInCu while still improving the thermal heat transfer

Table 7

Vibration Testing - SEM-E Format (0.100"/2.5 mm Thick)

Material	Natural Frequency (Hz)	G	Transmissibility (output G/ input G)	Double Displacement (in)
Al6061T6	530	265	8.8	0.194
Al6063 /P130(35%)	510	138	4.6	0.010
AlSiC(65%)	498	120	4.0	0.010
AlBeMet 162	542	170	5.7	0.011
E60	720	56	1.9	0.002

from the center of the core to the wedge locks. This would further decrease the weight of the system by another 30% over the absolute density difference in the materials.

Fabrication Technologies

Coatings: **E Materials** without coatings have similar corrosion resistance to aluminum, but for severe environments such as salt fog, the material needs a protective coating.

Like most metals, **E Materials** can be coated in a number of ways, including electroless or electrolytic nickel plating, chrome plating, copper plating, and gold or silver plating for brazing or soldering operations.

E Materials are also used as a constraining core in double sided surface mount packaging. This typically requires the bonding of PWB's to the core.

The surface of the core must provide a reliable bond area so that there is good adhesion between the PWB and the core. If there is a bond failure, it must be in the cohesion between the PWB and the coating, not the core. **E Materials** can be coated with chem film/alodine, an epoxy paint called BR 127, nickel plating, cadmium plating or copper plating for enhanced bond strength. The typical lap shear strength of a BR 127 primed E60 core is 3200 psi.

Salt Fog Testing: **E Materials** without any coatings will corrode similarly to 606T6 Aluminum in a 3.5% NaC1 salt solution, approximately 0.02mg/ cm-cm/day. With properly applied coatings, chem film/alodine, electroless nickel, chrome, copper, etc. they will survive from 48 to 500 hours salt fog exposure, depending on the type of coating.

Joining: Many RF/Microwave packages need to be hermetic to at least 2 x 10^{-8} atm.cc.sec. Traditionally, this is accomplished by brazing, using AuSn or AuGe ring frames on to a baseplate such as is done with Kovar or CuMo. **E Materials** can be processed into hermetic packages in similar technologies by using AuSn or AuGe brazing of Kovar, Alloy 46 or 48 titanium ring frames on **E Materials** bases and then welding a lid on the package.

Health and Safety

Handling beryllium metal 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 beryllium metal, contact Brush Wellman Inc., Beryllium Products Division, at 1-800-862-4118.

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ENGINEERED MATERIALS

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