Development of Aluminum Beryllium for Structural Applications

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ABSTRACT

A newly developed family of Aluminum Beryllium (AlBeMet®) metal matrix composite materials has been developed for use in satellite structures to address the needs of the designer for lightweight, stiff, thermally stable structures. This paper will present an overview of the development of these metal matrix composite materials and their use in satellite structures.

Lightweight and high modulus Aluminum-Beryllium composites offer significant performance advantages over traditional aluminum and organic composite materials. Aluminum-Beryllium composites also can be fabricated using conventional aluminum machining, joining, and coating technologies thereby reducing the cost of the final assembly, and eliminating any special tooling or nondestructive testing (NDT) that is sometimes required when designing and fabricating structures out of fiber reinforced composites.

This paper will present the thermal, physical, and mechanical properties of these composites, as well as providing structural test data for satellite components that have utilized Aluminum-Beryllium materials, such as the ORBCOMM^{sm}[1] satellites.

Keywords: Metal Matrix Composites, aluminum-beryllium, AM162H, AlBeMet®, specific stiffness, stability, fatigue strength, density

INTRODUCTION

Recent advances in the telecommunication and remote sensing industry, greater pointing accuracy, improved resolution, and increased number of satellites in a constellation plus launch costs that range from $10-$25,000/Lb ($4500-$11,300/Kg), have pushed the satellite designer into looking for better and less costly methods of sending satellites into orbit, while at the same time reducing the weight of the system and increasing the performance. To address these needs, Wellman in 1990, re-developed the aluminum-beryllium composite originally developed in the late 1960's by Lockheed under the trade name of "Lockalloy"[2]. This material had extensive research conducted into the mechanical and physical properties and the result was the successful use of the material in the YF12 and Minuteman Missile systems. Production difficulties in the 1970's limited the composite material to a few specialized applications and by the mid 1970's the material was no longer commercially available.

While the original "Lockalloy" was no longer in production, there was continuing interest in the aerospace design community in the aluminum-beryllium metal matrix due to its unique combination of properties, stiffness of steel, 25% lighter than aluminum, while at the same time having the fabrication technologies that are used for aluminum. After three years of improved processing techniques and process controls for the production of the composite and improved mechanical properties compared to the original "Lockalloy", Materion Beryllium & Composites re-introduced the material, under the trade name of AlBeMet®, into the commercial marketplace in late 1990.

MATERIAL CHARACTERIZATION

Aluminum-beryllium (AlBeMet® AM162) is a powder metallurgy composite of Beryllium 62% by weight and 1100 series pure aluminum, 38% by weight. The powder is produced by gas atomization, which yields a spherical isotropic powder with a fine beryllium structure. The powder particle size is typically -74 Mesh. The powder is consolidated by either Cold Isostatic or Hot Isostatic Pressing (CIP/HIP) and then metallurgically worked by conventional metal working technologies such as extrusion, rolling, and forging. AlBeMet® 162 has been extensively characterized in the 3 product forms it is currently available: extrusions, sheet, and Hot Isostatically Pressed (HIP). All 3 product forms have been approved and assigned SAE Aerospace Material Specifications (AMS) by the SAE committee. The specifications, which are a "S or A" allowable design basis, are AMS 7911 (HIP), AMS 7912 (extruded), and AMS 7913 (sheet). Over 700 production lots of powder have been produced for input into extrusions, sheet rolling, or HIP.

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PHYSICAL PROPERTIES

The principal interest in the use of AlBeMet® for satellite structures is the material's density, 0.076 Lb/cu.in. (2.10 g/cc), and modulus of elasticity 28 Msi (193 Gpa), or specific stiffness 4.1x 6061 T6 aluminum, and the ability of that property to reduce weight in the system and improve the first mode frequency of the structure (Table 1). As demonstrated in the use of AlBeMet® 162 and 150 for the ORBCOMM spacecraft[1], the increased specific stiffness allowed the structure to survive the Pegasus launch loads of 600 g's at 1000 Hz. Also for a stack of eight satellites in a launch, the bending frequency could be no less than 20HZ, and a maximum deflection under dynamic loading of no greater than 6.3mm (0.25 in) in order to avoid violating the Pegasus fairing envelope.

Table 1 - Comparison Properties of Selected Aluminum & AlBeMet® AM162 Wrought

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 (ppm/F)	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)

MECHANICAL PROPERTIES

Tensile The mechanical properties of AM162 have been extensively characterized in all three product forms, but a significant design database has been developed for the extruded product form[3]. 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. 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 the ASTM-E8 guidelines. The room temperature typical tensile properties are given in Table 2. The room temperature tensile strength of the wrought forms of AM162 compares favorably to 6061T6 aluminum, and is less than the 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. Also the spacecraft structure needed ductility in the material in order to accommodate the shock loads at the interface of the non-explosive separation bolts and the spacecraft, and the release of the pre-load energy on the bolts[1]. Like many metals, the tensile properties increase with decreasing temperature and decrease with increasing temperature. Also, there did not appear to be any preferred orientation of the tensile properties as a function of work direction or temperature.

Table 2 - Typical Room Temperature Tensile Properties 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

NOTCHED STRENGTH/PIN BEARING STRENGTH

There is no observable notch brittleness in AM162 extruded material. The strength ratios for all conditions were greater than one, with a stress concentration factor of Kt 3. The sharp-notch strength to yield-strength ratio (NRS) values was 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[2], NRS ratios of 0.98, there may be some notch sensitivity in the AM162 sheet material; this will be tested in the future. The notch strengthening indicated in the AM162 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 AM162 material.

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	556 (80.8)	1.5		NT
195°C T	482 (70.0)	1.3		
21°C L	513 (74.4)	1.6	8.9	349 (50.6) L
21°C T	435 (63.1)	1.3	6.4	333 (48.3) T
200°C L	641 (50.3)	1.6		NT
200°C T	344 (50.0)	1.3		

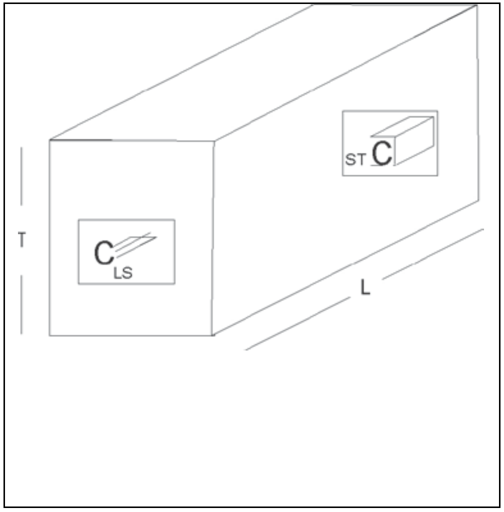
FATIGUE PROPERTIES

The fatigue properties of AlBeMet® 162 extruded material has been tested using the Krause rotating beam fatigue test utilizing fully reversed cycles with a R=0.1. The fatigue limit, 1 x 10^7 cycles, was about 207 MPa (30Ksi) in the longitudinal direction and 165 MPa (24Ksi) 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. While this is not as important for satellite structures, where they see limited stressed cycles, it was useful in the design of the ORBCOMM satellite. It allowed them to design up to the yield strength with very little concern that the on ground testing would fatigue the structure prematurely.

STRESS CORROSION CRACKING

AlBeMet® 162 sheet and extruded products have been tested for stress corrosion by Materion Beryllium & Composites and independent laboratories like European Space Agency (ESTEC) materials laboratory. The testing at Materion Beryllium & Composites 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 (4) orientations in multiple extrusion lots: transverse longitudinal (TL), longitudinal transverse (LT), longitudinal short transverse (LS), and short transverse (ST). (See figure 1.) The rings were then loaded under a constant strain.

Figure 1



The testing at ESTEC was done utilizing the ASTM E8-m subsize specimen and was 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, which was repeated over a 30 day period. This was done to both sheet and extruded material. These results, as seen in Table 4, indicate that none of the specimens failed during the 30 days of testing, and in subsequent tensile testing no degradation, even a slight increase in mechanical strength, was observed[4]. ESTEC/ESA have given their approval for the use of AlBeMet® 162 and 150 grades for use on satellite structures for European spacecraft. Since then, Alenia has applied the material on a mechanism for the Hot Bird Satellite.

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	Max Depth of Pits µm
AM150 RL	244.5	356.8	398.6	1.3	167.3	No failure	120
AM150 RT	244.5	344.4	391.5	2.23	176.2	No failure	20
Avg	244.5	350.6	395.1	1.77	171.8		
AM162RL	291	411	425.1	1.0	198.0	No failure	120
AM162RT	291	403	408.1	1.0	244.6	No failure	280
Avg	291	407	416.6	1.0	221.3	No failure	

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 2x. 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 AM150 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 Materion Beryllium & Composites 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 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 also is useful for adhesive bonding of structures together like was done for the ORBCOMM honeycomb panels is BR127, a sprayed on adhesive primer. 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 a alcohol solution to prepare it for active bonding. This coating eliminates the need for the final user to do anything to the AlBeMet® bare surface prior to bonding.

<u>Joining Technologies</u> 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 current work being done on laser welding technology[7]. Table 5 indicates the typical values obtained utilizing these processes, based on limited test data. There is extensive work being done in this area under joint funding by Materion Beryllium & Composites and DARPA, and the data/processes should be available in early 1998.

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)

Design joints for AlBeMet® materials is quite different from those using aluminum. Aluminum usually fails in a ductile manner, so bending occurs before failure, which usually occurs in the joint. With AlBeMet® materials, the metal is stiffer, so the joint is 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[1].

Figure 2 – ORBCOMM Satellite Assembly

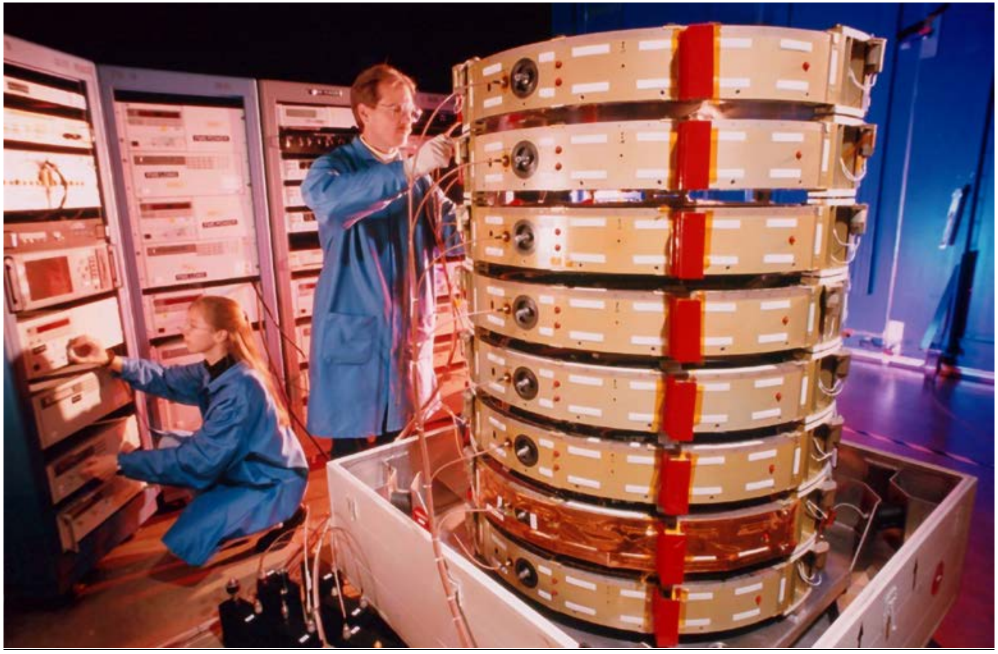
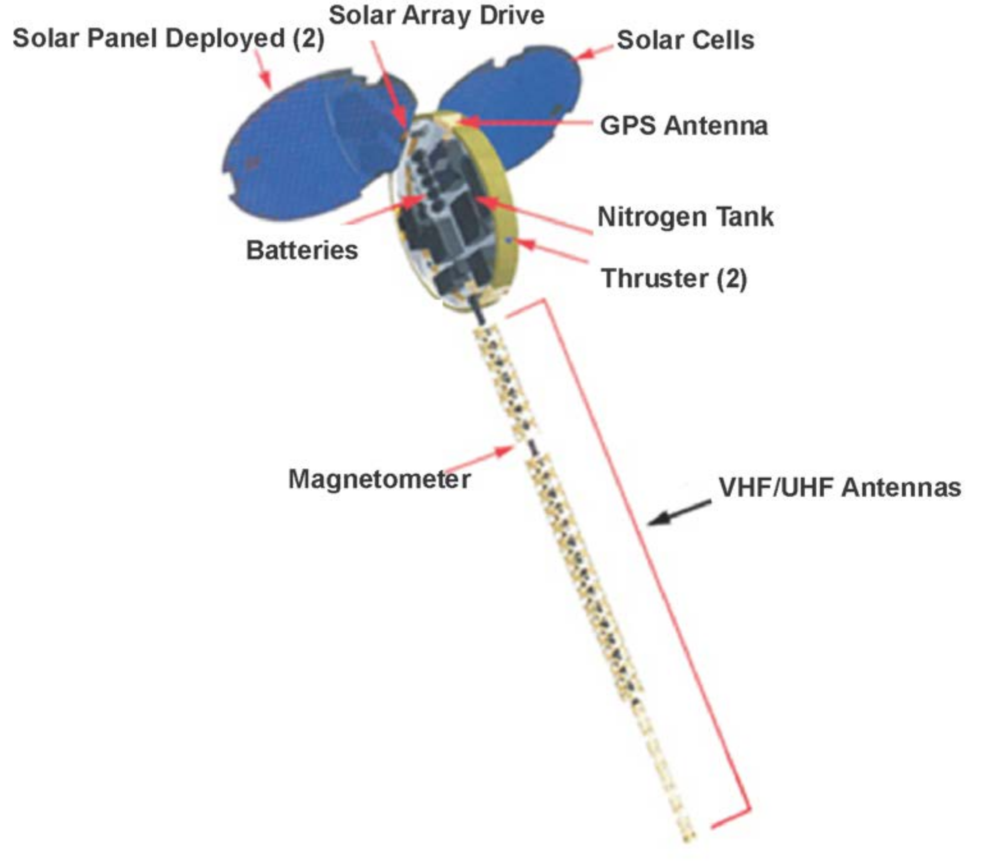


Figure 3 – ORBCOMM Spacecraft Configuration



ORBCOMM SPACECRAFT CONFIGURATION

Orbital Sciences expects to launch 28 Low Earth Orbit (LEO) satellites that will make up the ORBCOMM constellation. This constellation will provide telecommunication messaging between any two points on the globe, as well as providing global positioning navigation services.

The spacecraft consists of three major components as depicted in the schematic in figure 3:

- A 1.04m diameter by 152.5mm high housing that contains the spacecraft's computers, attitude control section, and communication payload.
- Two deployable solar panels for providing power to the spacecraft.
- A segmented, deployable boom supporting the antennas for communication with the ground stations.

The primary structural spacecraft ring is made from three arched, 25mm (1 in.) thick panels that are a bonded honeycomb using AlBeMet® sheet bonded to 5052 aluminum honeycomb. These are fastened together by three separation brackets made from AlBeMet® 162 extruded material to provide the stiffness and strength needed for holding the separation bolts and shear bearings between the individual spacecraft when configured for launch. The four gusset panels made from dip-brazed AlBeMet® sheet, connect the upper and lower flanges to provide rigidity to the structure. These also provide a connection between the payload shelf to the primary spacecraft ring. Adhesive-bonded AlBeMet® is also used for the rectangular tube that is used as the support structure for the antenna boom segments[1].

The primary AlBeMet® components on the ORBCOMM satellite are:

- Primary spacecraft ring
- Three separation brackets
- Four gussets
- Antenna boom support structure

ORBCOMM COST STUDY

Before Orbital Sciences committed to use AlBeMet® for the main components on the ORBCOMM spacecraft, they determined the cost effectiveness of using the material versus composites, magnesium, and aluminum, traditional materials used in spacecraft structures. To do this comparison, they used a current spacecraft, Micro Lab fabricated from magnesium that they had developed specific cost data on during recent fabrication and launch. They evaluated the use of unidirectional graphite/epoxy composites and decided that the material's anisotropic properties would be a design problem in the separation brackets. Those brackets require thick sections and isotropy of properties to withstand the separation bolt preload forces.

Table 6

Spacecraft	**Unit**	**ORBCOMM**	**Microlab**
Material		AlBeMet®	Magnesium
Cost*	$	$23,000	$30,000
Weight	Kg (Lb)	4.54 (10.0)	7.62 (16.8)
Unit Cost	$/Kg ($/Lbm)	5000 (2300)	4000 (1800)
Modulus	Gpa (msi)	158 (23)	43.4 (6.3)
Density	g/cc (Lbm/in^3)	2.1 (0.079)	1.7 (0.065)
Specific Stiffness	10^6m (10^6 in)	7.39 (291)	2.46 (97)
Launch Cost*	$/Kg ($/Lbm)	$20.6 ($45.3)	$34.5 ($76.2)

*Finished primary structure cost including all machining and post-fabrication costs.

*Assumes launch costs at $5000/Kg ($10,000/Lb)

FUTURE MATERIAL DEVELOPMENT

Materion Beryllium & Composites has recently investigated the use of magnesium additions to AlBeMet® in the form of a solid solution strengthener to potentially increase the strength of the material[5]. This work was a further study based on some preliminary work done in the 1970's by Lockheed[6]. The current work was performed on beryllium compositions ranging from 40 - 62%, and with additions of aluminum-magnesium alloys. For this paper, we will concentrate on the work done with the 62% beryllium and aluminum magnesium alloy additions.

Magnesium in the form of aluminum-magnesium powder was roll blended with the standard AlBeMet® 162 powder (AM162) (38% 1100 Aluminum/62% Beryllium), with a goal to achieve a 2-4% magnesium addition to mimic the work hardenable A 5056 aluminum. The composite powder blend was consolidated by Cold Isostatic Pressing (CIP) and subsequently extruded using a reduction ratio of approximately 10:1.

Figure 4 – Room Temperature Longitudinal UTS of Experimental Al Be Materials

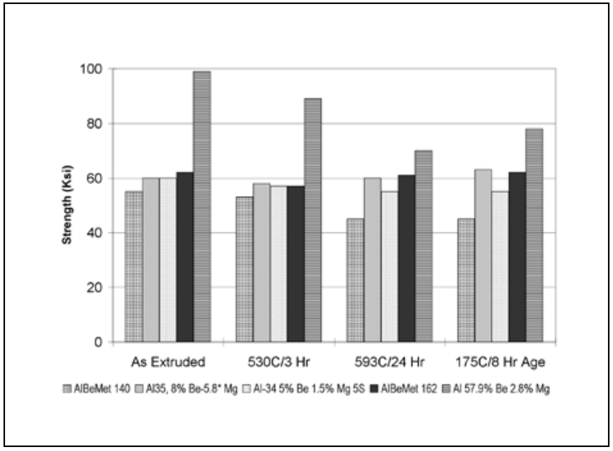
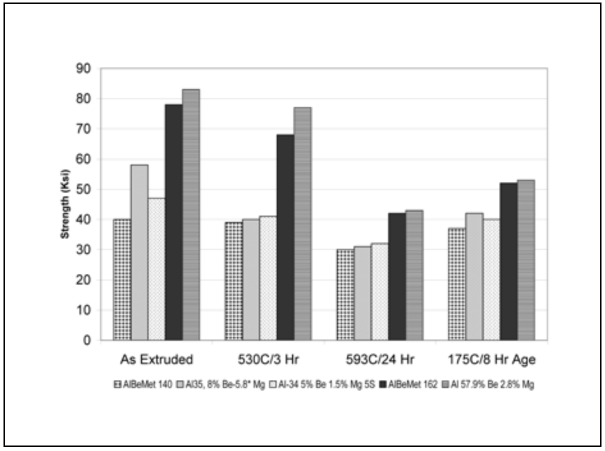


Figure 5 - Room Temperature Longitudinal 0.2% YS of Experimental AlBe Materials



Evaluation of the extrusions was performed on the following properties:

- Tensile properties based on heat treat response – 530°C (986°F); 593°C (1100°F); 175°C (350°F)
- Room temperature tensile properties per ASTM –e8
- Density
- Electrical Conductivity

As one would expect, density did not change with the addition of the 2-3% magnesium to the AlBeMet® 162 basic composition. The density was 2.11 g/cc before and after the heat treatment of either the 593°C or 175°C age for 8 hours. Modulus of the ternary alloy, Al-Be-Mg also did not change after heat treatment, as compared to the AlBeMet® 162 basic composition, which is 192 Gpa (28 Msi). The electrical conductivity of the ternary composition did decrease as compared to the AlBeMet® 162 basic composition. It was 34% IACS versus AM162's 42% IACS.

The highest tensile properties were found to be in the compositions with the highest beryllium content along with the magnesium additions. In fact, as shown in Table 7, the ultimate tensile strength of the as-extruded Al-57.9% Be-2.8% Mg was 679 MPa (98.6 Ksi) which is equivalent to some of the high strength aluminum alloys such as 7075T6. Yet with density 25% lower and a modulus that is almost 3 times higher, for a specific stiffness of 4X over the aluminum, with equivalent strength. Also, the yield strength increased with the additions of the magnesium, and this was observed at all heat treat cycles. The elongation of the ternary composition, Al-57.9% Be-2.8% Mg, did not improve over the base material, AM162, in the as-extruded condition. The typical values for AM162 are 3% in the as-extruded condition and 9-10% after a 593°C heat treatment for 24 hours. The ternary composition had elongation after the heat treatment of 6%.

CONCLUSIONS

1. AlBeMet® 162 material has been fully characterized and is a production material.
2. AlBeMet® 162 has been successfully used on the ORBCOMM spacecraft as a structural material.
3. AlBeMet® 162 showed no degradation after extended vibration loads that are typical of the Pegasus launch vehicle.
4. AlBeMet® has been approved by ESA/ESTEC to be used on European satellites.
5. Work on a higher strength AlBeMet® shows promise and additional work will be required before it can be a production material.

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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.