ALUMINUM-BERYLLIUM ALLOYS FOR AEROSPACE APPLICATIONS

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ABSTRACT

A family of low density - high elastic modulus aluminum-beryllium alloys is under development in order to meet the requirements of advanced aerospace designs. These alloys are aluminum based with 10%-75% beryllium and combine the high specific stiffness of beryllium with the ductility and ease of fabrication of aluminum. Densities ranging from 2.0 to 2.58 g/cc with excellent strength and ductility have been achieved.

The family of AlbeMet™ alloys under development was manufactured by both powder and ingot metallurgy techniques. Property characterization of extruded bar and rolled sheet included tensile, fatigue and fracture mechanics evaluation. The dependence of microstructure and properties upon composition and fabrication method, as well as upon third element additions is described.

Keywords: AlbeMet™, Aluminum, Aluminum-Beryllium Alloy, Beryllium, Lightweight, Modulus

1. INTRODUCTION

Development work performed in the 1960's[1] showed that the Al-Be alloy system had the potential to produce a family of lightweight materials with the combined attributes of the high modulus and strength of beryllium and high ductility and fracture toughness of aluminum. Beryllium is one of the lightest aerospace structural materials with a density of 1.85 g/cc (0.067 lb/cu.in.) while aluminum's density is approximately 45% higher at 2.7 g/cc (0.097 lb/cu.in.).

Aluminum and beryllium form a eutectic at a composition of 2.5%Al and a temperature of 644°C (1191°F)[2]. The terminal solid solution shows highly limited solubility of beryllium in aluminum and no solubility of aluminum in beryllium (Figure 1). This gives rise to the potential to treat the alloy as a composite engineered material. Prior data published[3] on rolled P/M Al-62wt%Be (Table 1), showed typical properties of the alloy after heat treatment at 600°C (1100°F).

2. PROCEDURE

Aluminum-Beryllium alloys of three compositions were produced by powder and ingot metallurgy methods. The compositions investigated included Al-20wt%Be, Al-40wt%Be and Al-62wt%Be. The aluminum used as reference for the study was grade AA1100 which is 99% minimum pure. Aluminum from grade AA6061 was used to make minor additions of third element additions such as magnesium and silicon in the ingot cast material.

2.1 Powder Metallurgy

Two compositions were studied using the powder metallurgy approach. Inert gas atomization was used to produce prealloyed Al-Be particles. These particles exhibited a fine dispersion of Al and Be (Figure 2). The typical beryllium dendrite size was on the order of 1 to 10 microns. Typical -100 mesh (<149 micron) powder chemistries showed that there were minor concentrations of other elements (Table 2).

The powder was consolidated and worked by one of two methods. These were extruded into a rectangular bar by first encapsulating a cold isostatically pressed (CIP'd) billet within a copper can or by rolling a billet made from hot isostatically pressed (HIP'd) powder. Extrusion was performed with a 12:1 cross section area reduction for the Al-40wt%Be and 7:1 area reduction for the Al-62wt%Be. Rolling of both HIP'd alloys was performed to a reduction of 95%.

Proc. Internat. Symp. 'Advanced materials for lightweight structures', ESTEC, Noordwijk, The Netherlands, 25-27 March 1992 (ESA

SP-336, October 1992)

Table 1. Room Temperature Mechanical Properties Rolled Al-62wt%Be - Heat Treated 6000 for 100Hrs

0.2% YS - MPa ksi	242-262 (36-38)
UTS - MPa ksi	324-358 (47-52)
Elongation %	5 -12
Modulus - GPa (Msi	186-213 (27-31)

The worked material was then heat treated at (593°C) 1100°F for 24 hours. Density, longitudinal tensile properties and microstructure of both the extruded bar and rolled sheet were determined. Fracture toughness and rotating beam fatigue properties of the extruded bar was determined.

2.2 Ingot Metallurgy

Two alloys containing Al-20wt%Be and Al-40wt%Be were produced by vacuum induction melting and static casting followed by hot forging and hot rolling. The resultant sheet was 95% the thickness with respect to the as-cast condition. Prealloyed aluminum AA6061 was used to determine the effect of adding ternary elements to these alloys. AA6061 contained nominally 1%Mg, 0.6%Si, 0.28%Cu and 0.2%Cr

The hot rolled sheet was annealed at (500°C) 930°F for 16 hours prior to evaluation. Density, microstructure and longitudinal tensile properties were evaluated.

3. RESULTS AND DISCUSSION

3.1 Powder Metallurgy

Density of fully consolidated powder ranged from 2.26 g/cc to 2.09 g/cc (0.082 lb/cu.in. to 0.076 lb/cu.in.) for Al-40wt%Be and Al-62wt%Be, which is what one would calculate based upon volume fraction rule-of-mixture (Figure 3).

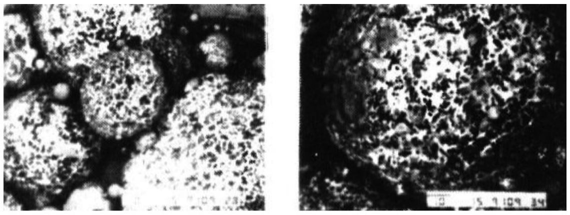
Metallography of the alloys worked by the two methods showed that extrusion (Figure 4) produced a microstructure with higher aspect ratio as compared to the rolled material (Figure 5). Comparison of the microstructure between Al-40wt%Be and Al-62wt%Be showed that the aspect ratio of the beryllium was greater in the higher beryllium alloy.

Table 2. Typical Atomized Powder Chemistry -100 Mesh (<149 micron)

TARGET	Al-40wt%Be	Al-62wt%Be
Al (%)	58.1	35.7
Be (%)	40.1	63.4
BeO (%)	0.24	0.30
C (%)	0.048	0.056
Fe (ppm)	570	730
Mg (ppm)	<100	120
Si (ppm)	225	300

Fig. 2. Backscatter Electron Image of Atomized Al-Be Powder. The aluminum appears light, the beryllium appears dark.

ALUMINUM-BERYLLIUM DISTRIBUTION
IN ATOMIZED POWDER



Al-62wt%Be Al-40wt%Be

FIG. 3. Density of Al-Be Alloys. Rule of mixture (ROM) and measurements.

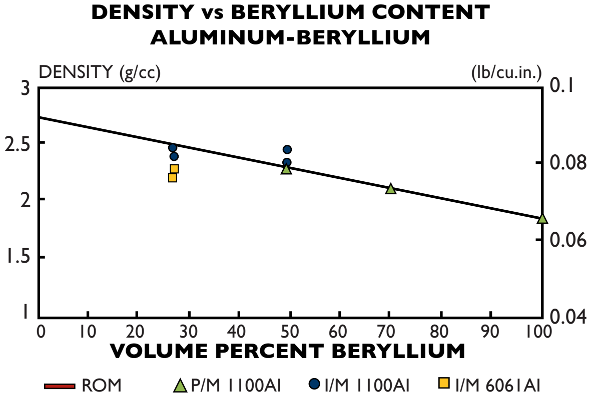
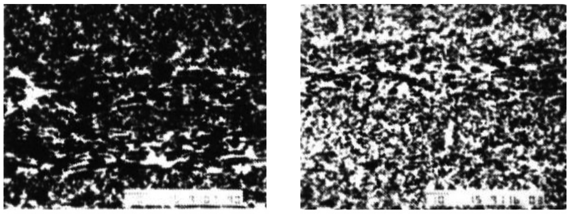


Fig. 4. Backscatter Electron Image of Extruded Al-Be Powder. The aluminum appears light, the beryllium appears dark.

MICROSTRUCTURE OF CIP/EXTRUDED
ATOMIZED POWDER



Al-62wt%Be Al-40wt%Be

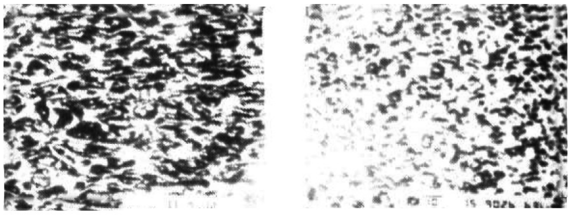
Yield strength was about 205 MPa (29 ksi) for Al-40wt%Be regardless of consolidation or working method (Figure 6). Yield strength for Al-62wt%Be was about 344 MPa (50 ksi) for material extruded and 275 MPa (40 ksi) for rolled. The effect of different microstructural characteristics and resultant yield strength differences were more apparent in the Al-62wt%Be composition, which contained more beryllium compared to the Al-40wt%Be.

The effect of higher beryllium content on properties was further shown. Ultimate tensile strength (Figure 7) of Al-40wt%Be was 275 MPa (40 ksi) while the tensile strength of the Al-62wt%Be was higher by 50% at 410 MPa (60 ksi).

Elongation clearly improved with more aluminum and higher aspect ratio microstructure (Figure 8). Elongation of Al-40wt%Be was about 14% for rolled material and about 18% for extruded material. Elongation of Al-62wt%Be consolidated and worked by either method was about 12%.

Fig. 5. Backscatter Electron Image of Rolled Al-Be Powder. The aluminum appears light, the beryllium appears dark.

MICROSTRUCTURE OF HIP/ROLLED
ATOMIZED POWDER



Al-62wt%Be   Al-40wt%Be

Elastic modulus (Figure 9) of Al-40wt%Be was about 136 GPa (20 Msi). The elastic modulus of Al-62wt%Be was about 195 GPa (28 Msi). Modulus of both materials was slightly higher by about 10% in the rolled form when compared to the extruded form.

Rotating beam fatigue specimens were machined from the extruded bars with axis orientation parallel to the longitudinal axis of the bar. Fatigue endurance limit, or run out at 10° cycles was about 137 MPa (20 ksi) for Al-40wt%Be and 206 MPa (30 ksi) for Al-62wt%Be (Figure 10).

Fracture toughness tests on the extruded bar were made using 2.54 cm (1-inch) wide specimens per ASTM method E399. The specimens were oriented in the LT direction. K_{IC} of the Al-62wt%Be extrusion was 13.8 MPa-m$^{0.5}$ (12.6 ksi-in.$^{0.5}$). A valid K_{IC} measurement of the Al-40wt%Be could not be measured because the test failed to meet validity requirement of $P_{MAX}/P_Q < 1.10$. A conservative K_Q value of 12.0 MPa-m$^{0.5}$ (10.89 ksi-in.$^{0.5}$) was obtained for the LT orientation of Al-40wt%Be. A residual strength ratio, Rsc of 1.76 indicated that if K_{IC} was obtained, an estimate would be in excess of 27 MPa-m$^{0.5}$ (25 ksi-in.$^{0.5}$). It cannot be overemphasized that this is only an estimate.

FIG. 6. Longitudinal Yield Strength of Consolidated Al-Be Powder.

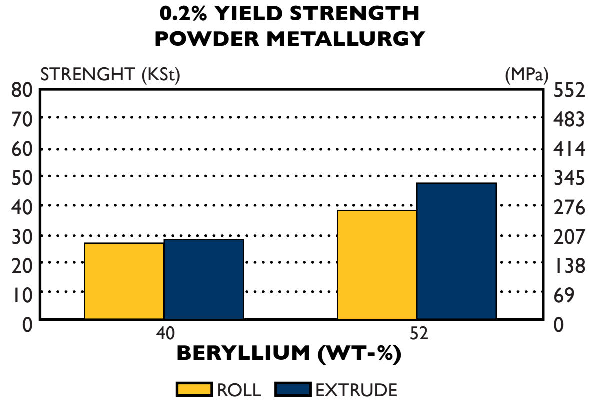


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FIG. 7. Longitudinal Ultimate Tensile Strength of Consolidated Al-Be Powder.

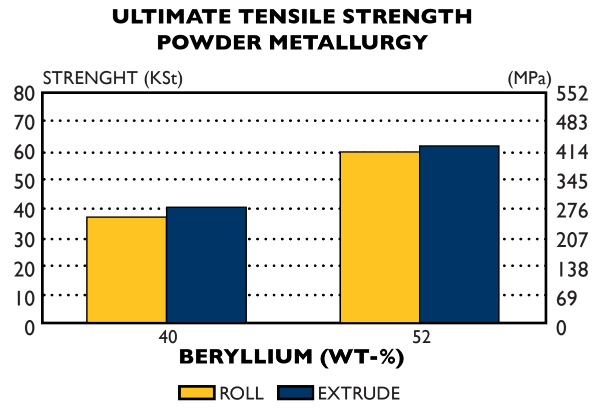

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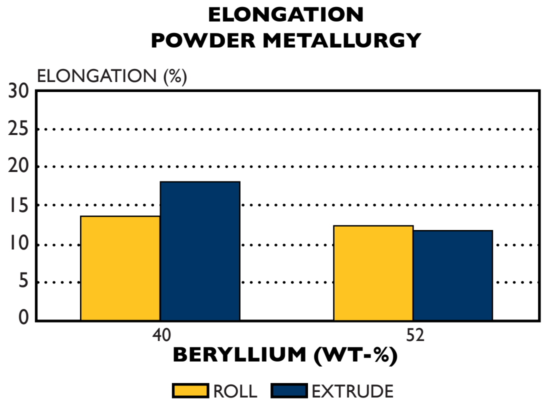
FIG. 8. Longitudinal Elongation of Consolidated Al-Be Powder.



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3.2 Ingot Metallurgy

The densities of the as-cast materials and hot rolled sheet (Figure 3) compared well with theoretical densities calculated by the rule-of-mixtures. The Al-20wt%Be composition had a

density of 2.44 g/cc (0.088 lb/cu.in.) while Al-40wt%Be had a density of 2.27 g/cc (0.082 lb/cu.in.).

The beryllium dendrite size was approximately 60 microns with secondary dendrite arm spacing ranging from 15 to 40 microns (Figure 11). After 95% reduction, the beryllium dendrites were broken up and deformed into elongated fibers having an aspect ratio of about 10:1 (Figure 12).

Improvement in longitudinal yield and ultimate tensile strengths with increased levels of beryllium content was observed (Figure 13 and Figure 14). Yield strength of the binary alloy increased from 241 MPa (35 ksi) for Al-20wt%Be to 289 MPa (42 ksi) for Al-40wt%Be. Ultimate tensile strength increased from 269 MPa (39 ksi) for Al-20wt%Be to 386 MPa (56 ksi) for Al-40wt%Be.

FIG. 9. Longitudinal Elastic Modulus of Consolidated Al-Be Powder.

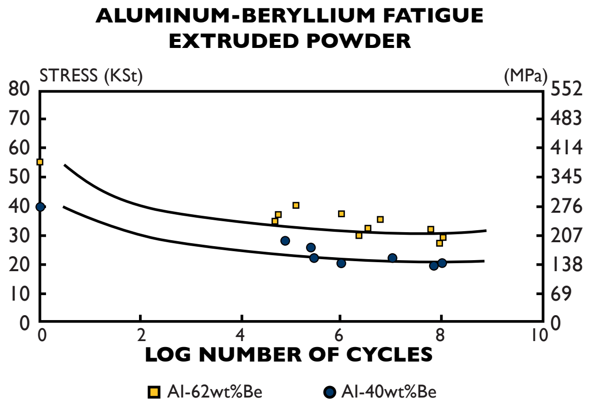

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FIG. 10. Fatigue Properties of Extruded Al-Be Powder.

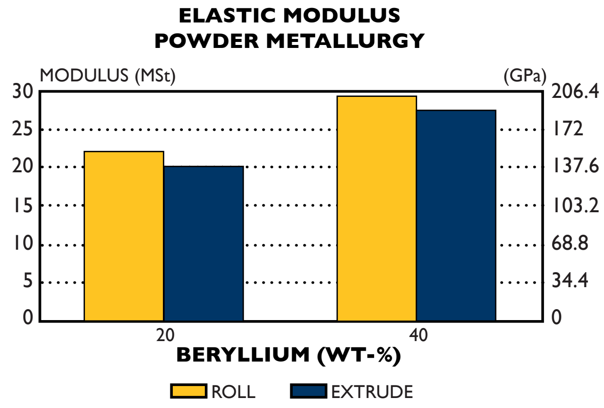

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Fig. 11. Microstructure of Ingot Cast Al-Be Alloys.

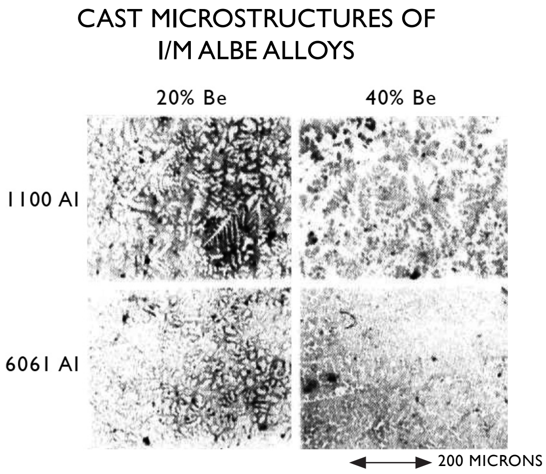
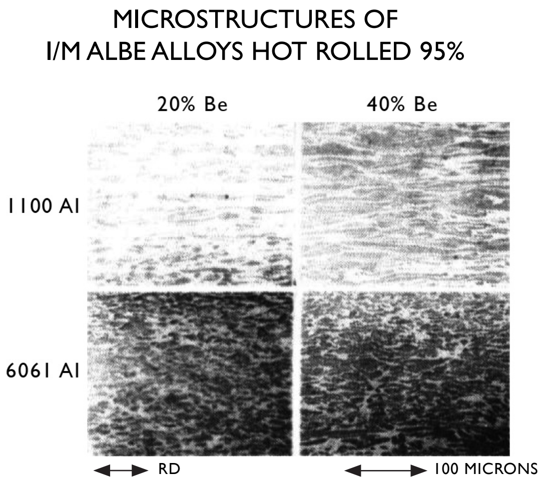


Fig. 12. Microstructure of Rolled Cast Al-Be Alloys.



The effect of ternary alloying elements was also observed. Yield strength of Al-40wt%Be increased from 289 MPa (42 ksi) to about 414 MPa (60 ksi) with the addition of alloying elements. Ultimate tensile strength increased from 379 MPa (55 ksi) to 462 MPa (67 ksi) in Al-40wt%Be.

The data indicated, contrary to what was expected that higher beryllium concentration improved elongation going from 8% in Al-20wt%Be to 17% in the Al-40wt%Be (Figure 15). This effect may have been the result of experimental error. Elongation of >20% was expected in Al-20%wtBe. Elongation dropped from 17% to 7% when the ternary elements were added to Al-40wt%Be.

Elastic modulus was found to be about 124 GPa (18 Msi) for Al-20wt%Be sheet and about 145 GPa (21 Msi) for Al-40wt%Be (Figure 16). Good agreement was shown when compared to the elastic modulus predicted by the rule-of-mixture.

4. CONCLUSIONS

1. A low density aerospace material with combined attributes of strength, modulus and toughness can be engineered from aluminum/beryllium by either powder metallurgy or ingot metallurgy.
2. Higher concentrations of beryllium reduces density, increases strength, but decreases ductility.
3. Microstructure as a result of cast origin and working, effect mechanical properties.
4. Ternary alloying elements were found to hold potential to increase strength but decrease ductility.

FIG. 13. Longitudinal Yield Strength of Rolled Cast Al-Be Alloys.

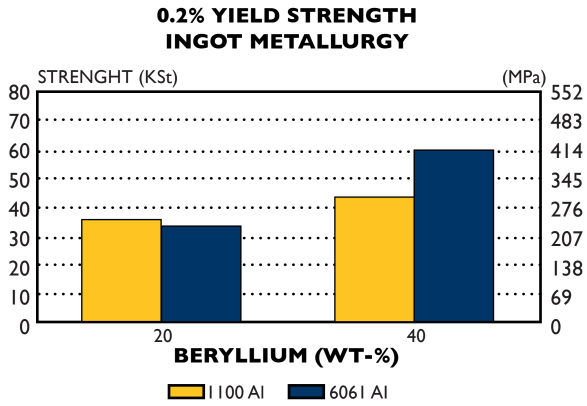


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FIG. 14. Longitudinal Ultimate Tensile Strength of Rolled Cast Al-Be Alloys.

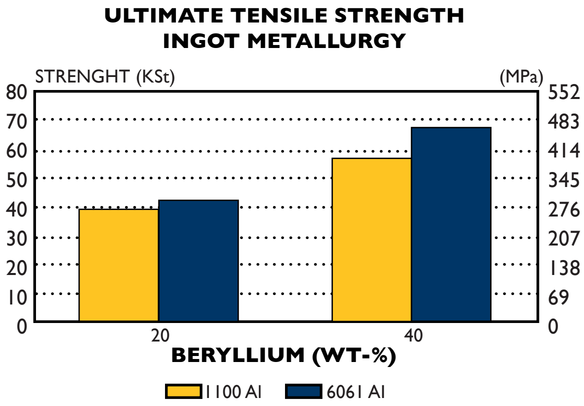

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FIG. 15. Longitudinal Elongation of Rolled Cast Al-Be Alloys.

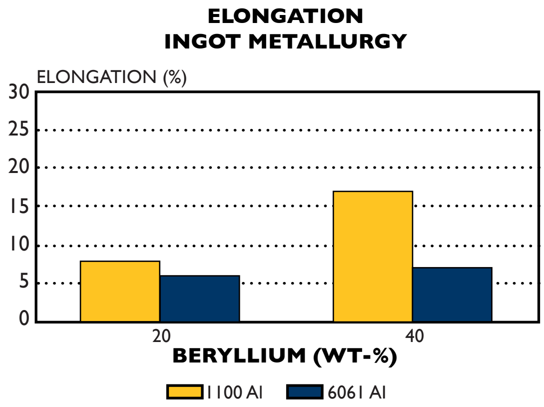

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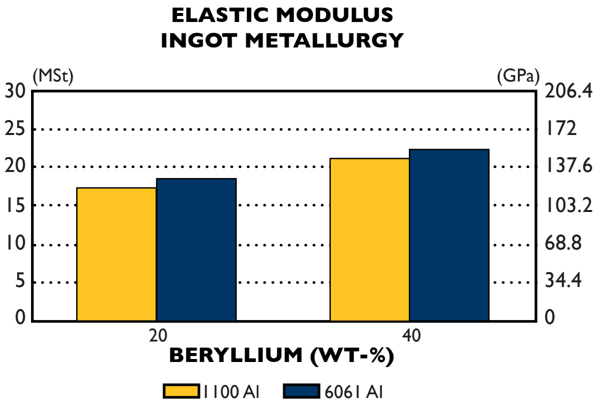
FIG. 16. Longitudinal Elastic Modulus of Rolled Cast Al-Be Alloys. Heavy line is predicted from rule of mixtures (ROM).



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5. REFERENCES

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3. London, Gilbert, "Alloys and Composites," Beryllium Science and Technology, Volume 2, ed. Dennis Floyd and John Lowe, Plenum Press, NY, 1979.

Note:
Handling Aluminum-Beryllium Alloys 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 formation on safe handling practices a technical data on Aluminum Beryllium Alloys, contact Materion.

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