MATERION

DATA SHEET

Mechanical and Thermal Semi-Solid Metal Forming of Beryllium-Reinforced Aluminum Metal Matrix Composites

Warren Haws, Larry Lane, James Marder, Materion Beryllium & Composites
Norm Nicholas, Formcast

A Powder Metallurgy (PM) based, Semi-Solid Metal (SSM) forming process has been developed to produce low cost near-net shapes of beryllium-reinforced aluminum Metal Matrix Composites. Beryllium acts as a reinforcing additive to the aluminum, in which there is nearly no mutual solid solubility. The modulus of elasticity of the Metal Matrix Composites dramatically increases, while the density and thermal expansion coefficient decreases with increasing beryllium content. The material is suitable for complex thermal management and vibration resistance applications, as well as for airborne components which are density and stiffness sensitive.

The forming process involves heating a blank of the material to a temperature at which the aluminum is semi-solid and the beryllium is solid. The semi-solid blank is then injected without turbulence into a permanent mold. High quality, near net shape components can be produced which are functionally superior to those produced by other permanent mold processes. Dimensional accuracy is equivalent to or better than that obtained in high pressure die casting.

Cost effectiveness is the primary advantage of this technique compared to other forming processes. The advantages and limitations of the process are described. Physical and mechanical property data are presented, as well as directions for future investigation.

INTRODUCTION

Beryllium and its alloys with aluminum present a series of materials which uniquely combine low density, high elastic modulus and excellent thermal conductivity and diffusivity (1). The elastic modulus of beryllium, 303 GPa (44×10^6 psi), exceeds that of other low density aerospace materials such as magnesium, aluminum and titanium by factors of 8, 4 and 3 respectively. The density of beryllium, 1.85 g/cc (0.067 lb/in^3), is lower than any of these materials with the exception of magnesium.

In many critical applications, the modulus to density ratio, the specific modulus, is the figure of merit which drives material selection. Beryllium, and Metal Matrix Composites of beryllium which combine its high modulus and low density with other attributes such as ease of processing or improved fracture characteristics, are therefore quite attractive in aerospace structures (2) and other precision applications (3). In addition to structural performance advantages over common aerospace materials, beryllium also has very high thermal conductivity, 210 W/m-K (121 Btu/hr-ft-°F), and heat capacity, 1925 J/kg-K (0.46 Btu/lb-°F). Thermal conductivity is equal to or superior to most structural aluminum alloys. The heat capacity is twice that of aluminum and aluminum-based alloys. This property combination renders beryllium an excellent material for thermal management uses in satellite and aircraft avionics applications.

The AlBeMet® family of aluminum-beryllium Metal Matrix Composites combines the process flexibility of conventional aluminum Metal Matrix Composites with the unique characteristics of beryllium. In the solid state, there is only negligible mutual solubility of the two species (4). In many cases, the physical properties, including density, of a given AlBeMet® Metal Matrix Composites may be closely approximated by a volumetric rule of mixtures (ROM) calculation. This is illustrated in Figure 1, in which the relationship of elastic modulus is shown as a function of aluminum content in the aluminum-beryllium system. The addition of aluminum to beryllium is not performed simply to dilute the beryllium to a more easily processed form. The addition of aluminum imparts tolerance for the cryogenic environment, whereas the use of aluminum Metal Matrix Composites provides the opportunity to achieve properties which are not possible with either beryllium (5) or AlBeMet® with a pure aluminum matrix.

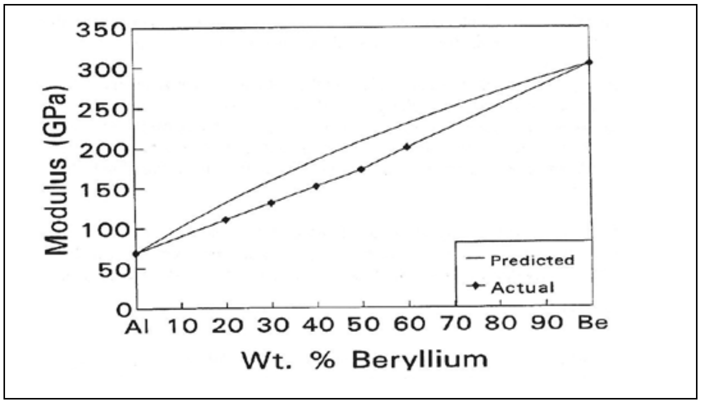


Figure 1. Modulus Comparison for AlBeMet® Metal Matrix Composites – Rule of Mixtures Calculation versus Actual Measurements

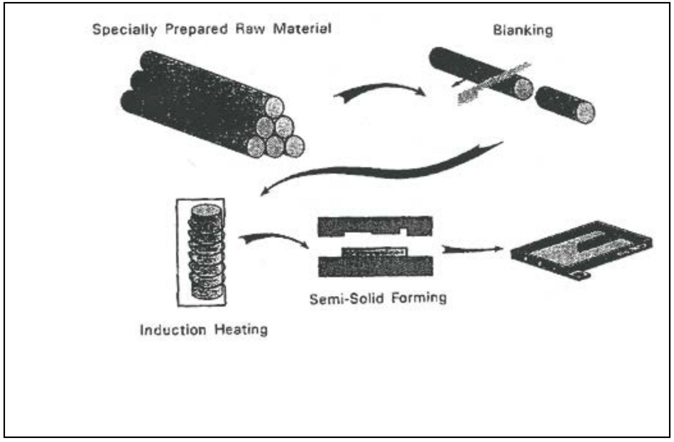
Net shape forming technology is of significant economic advantage to the production of complex components fabricated from high value raw materials. The advantages are derived from two sources. The first is the reduced machining cost which may result from proper application of a net shape process. The second is the reduction in the required material input when a net shape process is employed. These advantages become particularly significant when a high value raw material, such as beryllium or AlBeMet®, is involved. The reduced raw material requirement translates into reduced cleaning, sorting and recycling cost of chips and swarf in addition to the dross reduction in purchased material cost (6). Many processes have been investigated for their cost reduction potential in beryllium-rich materials (6,7). For beryllium itself, powder metallurgy routes, involving Hot Isostatic Pressing (HIP), Cold Isostatic Pressing/Sintering (CIP/Sinter) and Cold Press/Sinter (CP/Sinter) have been investigated. The first two of the above mentioned processes are capable of producing three dimensional shapes, whereas the third is most useful for two dimensional parts. However, each of these processes has limitations regarding process cost and component complexity and tolerance control

Recently, semi-solid metal (SSM) forming technology has been demonstrated for aluminum and copper Metal Matrix Composites (8). This process, based on original work at the Massachusetts Institute of Technology (MIT) (9), has been shown to be a very competitive net shape forming process for high quality aluminum Metal Matrix Composites. This paper describes the development of a SSM forming process uniquely adapted to the production of beryllium-modified aluminum Metal Matrix Composites. Using powder metallurgy based raw material feedstock, SSM forming provides a high speed, tight tolerance, high material yield process for the production of complex shaped parts from high value materials.

Semi-solid metal (SSM) processing is a unique forming process ideally suited for the manufacture of near net shape components from a variety of metal Metal Matrix Composites. By incorporating elements from both casting and forging, SSM forming provides a low cost production method for intricate components of exceptional quality. The basis for SSM is the special rheological behavior exhibited by the metal while in the partially solid/partially liquid condition. This behavior was originally discovered at MIT (9) in the early 1970's.

Through the use of high temperature viscometry, researchers found that semi-solid metals, with this special solid phase morphology, exhibited remarkably low shear strength even at relatively high fractions of solid. However, these same materials remained rigid and self supporting when at rest.

Based on this "quasi thixotropic" behavior, a process has been developed by which specially prepared aluminum-beryllium metal Metal Matrix Composites slugs, heated to a semi-solid condition, can be handled as solids but flow as viscous liquids upon injection into a die cavity. This process is schematically depicted in Figure 2.



When in the semi-solid condition, the Metal Matrix Composites forms a suspension of solid beryllium particles in a liquid aluminum Metal Matrix Composites matrix. Figure 3 shows a typical microstructure for the AlBeMet® Metal Matrix Composites precursor to the SSM process. The liquid allows the solid particles to flow easily past one another with minimal resistance. During the forming process, the semisolid slurry is injected into the die cavity using low pressure and speed in a laminar flow condition such that air and other contaminants are pushed to the perimeter and expelled. Once the die cavity is filled, high pressure is applied to feed shrinkage as the aluminum Metal Matrix Composites solidifies. The result of this turbulence-free filling behavior is porosity free parts of exceptional quality.

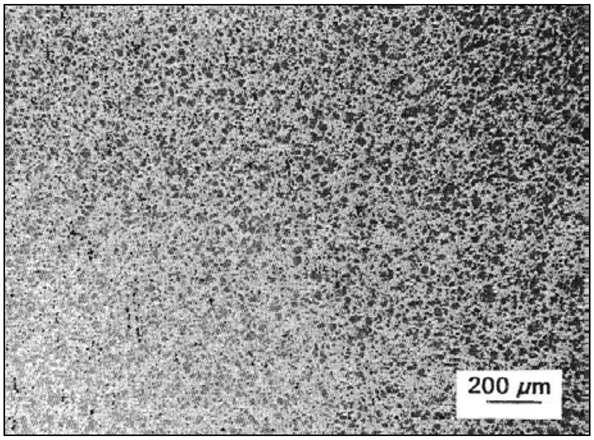


Figure 3. Microstructure of the Percursor AlBeMet® Metal Matrix Composites to the SSM Process, 30% Impact Ground Beryllium

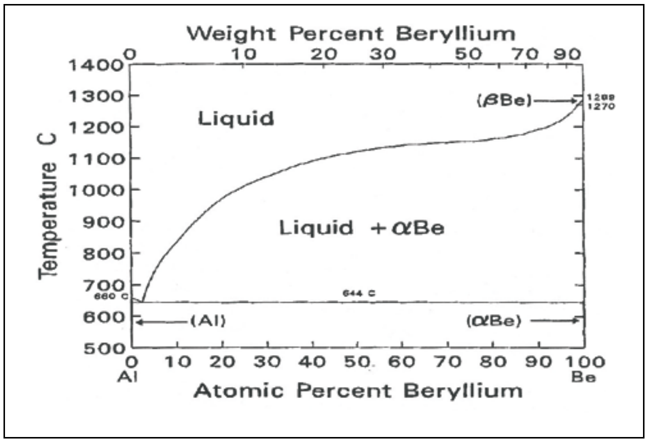


Figure 4. Aluminum-Beryllium Phase Diagram

The viscous nature of semi-solid materials allows solid reinforcing particles, such as beryllium, to be carried within the solid/liquid mixture to act as a reinforcing agent in the final part. Within the semi-solid slurry, the beryllium particles replace the solid phase of the aluminum thus requiring further melting to produce sufficient liquid for forming. Beryllium particles can be incorporated in high volume fractions such that all of the aluminum is melted.

MATERION DESCRIPTION

The beryllium-aluminum system is a simple eutectic system, as shown in the equilibrium diagram, Figure 4 (4). The maximum solid solubility of one component in the other occurs at the eutectic temperature, 644°C (1192°F). At lower temperatures the extent of solid solubility falls rapidly, into the parts per million range at room temperature. There is, however, a significant temperature difference in melting point of the pure constituents when mixed. It is this temperature difference that is used to advantage in the semi-solid metal (SSM) processing of Al-Be Metal Matrix Composites.

If the pure constituents are mixed and heated such that the aluminum constituent partially melts, while the beryllium remains solid, a semi-solid body can be formed. Since there is some solubility of beryllium in the molten aluminum, a strong interface between the two phases is produced due to the wetting of the solid beryllium particles by the molten aluminum. This allows semi-solid processing to be carried out with elemental input materials, while maintaining the rule of mixtures behavior characteristic of conventionally cast or consolidated prealloyed atomized powder input.

MATERIAL PREPARATION/POWDER PROCESSING

AlBeMet® represents a family of aluminum Metal Matrix Composites which contain beryllium as a second phase. The work done to evaluate the semi-solid processing of this family of Metal Matrix Composites concentrated upon A356 aluminum powder which was mixed with impact ground, -325 mesh beryllium powder. A356 was selected because it has been well characterized in semisolid processing studies. The 7% silicon content provides a wide freezing range, and eliminates the hot-shortness associated with pure aluminum. Aluminum Metal Matrix Composites 7075 and 6061 were also evaluated as matrix materials.

Both spherical (atomized) and impact ground beryllium powders were used in initial trials. Both powders exhibited satisfactory flow characteristics during forming operations. Impact ground powder was selected for use in the continued experiments for economic reasons.

A -200 mesh aluminum Metal Matrix Composites powder and a -325 mesh beryllium powder were mixed in a double cone blender to provide homogeneous input material. Care was taken to electrically ground and bond all components of the system, and an inert atmosphere was provided to minimize any explosion potential.

Once mixed, the blend was loaded into cylindrical rubber bags for cold isostatic pressing (CIP). A CIP pressure of 276 MPa (40,000 psi) was applied, resulting in a green density of approximately 85% of theoretical. The green preforms were then loaded into copper cans for extrusion. The loaded copper cans were degassed and sealed. The degassing was designed to remove any adsorbed moisture on the powder surfaces. The cans were then extruded, using an extrusion ratio of approximately 57:1. The extrusion can was removed, leaving a fully dense 19mm (0.75 inch) diameter AlBeMet® rod.

SEMI-SOLID METAL FORMING

The beryllium-reinforced aluminum input material produced in the previous section was then cut into slugs of the appropriate size required to fill the die cavity. The slugs were heated inductively to a semi-solid condition using a high frequency power supply and a specially programmed heating schedule. The material maintained an upright stance throughout heating even when at temperatures where the aluminum phase was completely liquid. Once in the semi-solid condition the slugs were transferred to the forming die by a mechanical robot arm. The transfer arm uses specially designed gripping jaws that contact the slug with a constant force such that it is not deformed when lifted. Low thermal mass unheated gripper jaws eliminate problems of sticking associated with high temperature heated grippers and prevent significant heat losses during transfer.

The semi-solid slugs are deposited on the die surface and injected by the downward action of a hydraulic ram into the die cavity. This can be via a gate and runner system or in some instances can be similar to a closed die forging process. In either case, care must be taken to ensure adequate distribution of the Metal Matrix Composites to the die cavity. After a brief freezing and cooling time, the die opens and the formed part is ejected, ready for the next cycle. The dies must be maintained at operating temperatures around 180°C (356°F) and the appropriate application of die release agents are required before each cycle.

Given the relatively low forming pressures and impact free injection process, new low cost tooling techniques have been implemented allowing rapid tool change and excellent tolerance control. After ejection from the die, the parts can be trimmed to remove gating systems if present and are ready for subsequent finishing. When aluminum Metal Matrix Composites matrices are employed this can include full heat treatment to optimize mechanical or physical properties. Examples of the parts formed are shown in Figure 5. Over 1000 of the connector cap/flange parts and over 1400 of the Sabots have been formed.

RESULTS & DISCUSSION

Physical Properties. Physical properties were measured on parts SSM formed at injection speeds of 350 to 650 (unit less dial reading) and at various forming temperatures using A356 + 30% beryllium. Most of the data reported is on parts formed from input slugs extruded at 57:1 reduction ratio, however, some input slugs were extruded at 37:1 reduction ratio. Density, modulus, and thermal conductivity were measured at room temperature and thermal expansion was measured from room temperature to 500°C (932°F).

Density. Density was measured on 282 specimens using the water immersion technique. The densities were averaged for each of the 36 unique combinations of injection speed, forming temperature, and preform extrusion reduction ratio. The average densities ranged from 2.354 g/cc (99.55% theoretical) to 2.361 g/cc (99.82 % theoretical). There did not appear to be any correlation between preform extrusion reduction ratio and density of the SSM formed component. The average densities are shown graphically in Figure 6 as a function of injection speed and temperature. The average density (calculated for all the data points) for 30% impact ground beryllium was 2.358 g/cc ± 0.005 (99.7% ± 0.2% theoretical). Within the forming conditions studied, there does not appear to be any correlation between injection speed or temperature and density.

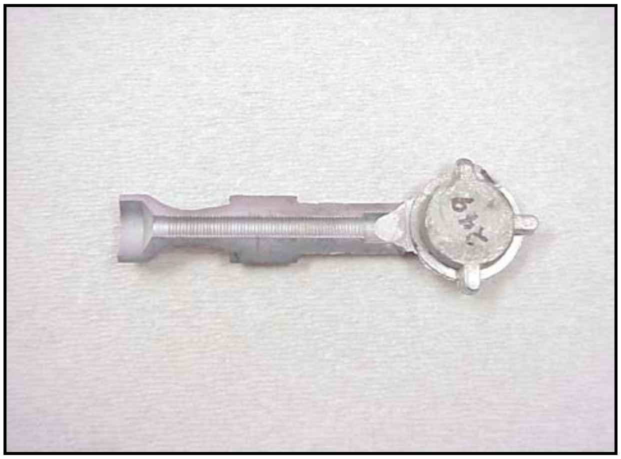


Figure 5 SSM Formed Parts for 30mm Bradley Fighting Vehicle Sabots

The average density for parts formed using 30% spherical beryllium was 2.360 g/cc ± 0.002 (99. 80% ± 0.04% theoretical). This average is slightly higher than the average for the impact ground powder. In addition the standard deviation of these data was much smaller than that of the 30% impact ground beryllium.

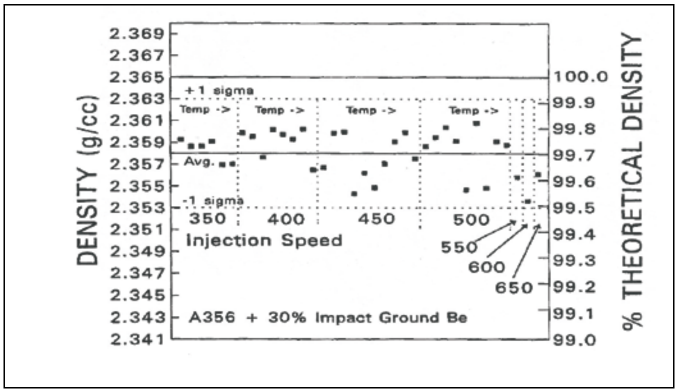


Figure 6. Average Densities of Semi-Solid Metal Formed Parts as a Function of Injection Speed and Forming Temperature

Density was also measured on 92 Sabots formed from A356 + 30% beryllium. The average density was 2.361 g/cc ± 0.004 (99.83% ± 0.17 %) of theoretical density.

Modulus of Elasticity. The modulus of elasticity is being measured at room temperature on duplicate specimens from each of the unique combinations of injection speed, forming temperature, and preform extrusion reduction ratio. This testing is still in progress.

Thermal Expansion. Thermal expansion was measured between room temperature and 500°C(932°F) on specimens containing A356 and 30% impact ground beryllium. Delta L/LO versus temperature data are presented graphically in Figure 7. The mean coefficient of thermal expansion (CTE) calculated between room temperature and 100°C (212°F) is about 18 x 10-6 cm/cm/°C (10 x 10-6 in/in/°F). This value is comparable to that calculated by rule of mixtures and those measured on wrought AlBeMet®.

Thermal Conductivity. Thermal conductivity was calculated from thermal diffusivity measurements made at room temperature using the Laser Flash Method for Thermal Diffusivity (ASTM E-1461, C 714) for specimens containing 30% beryllium. The data are presented in Table I. Heat capacity was calculated using a rule of mixtures calculation with 0.22 cal/g-°C (0.22 Btu/lb-°F) for A356 and 0.46 cal/g-°C (0.46 Btu/lb-°F) for beryllium. Measured density of the specimens was 2.360 g/cc (0.085 lb/in3). The average thermal conductivity of 4 measurements was 181 W/m-K (105 Btu/hr-ft-°F). This value is comparable to that calculated by rule of mixtures and those measured on wrought AlBeMet®.

Table I. Thermal Conductivity for SSM Formed Parts with 30% Impact Ground Beryllium

Specimen	Density	Thermal Diffusivity (cm2/s)	Calculated Heat Capacity (W-s/g-K)	Thermal Conductivity (W/m-K)
71-4A	2.360	0.629	1.222	181
71-4B	2.360	0.633	1.222	183
72-4A	2.360	0.629	1.222	181
72-4B	2.360	0.625	1.222	180

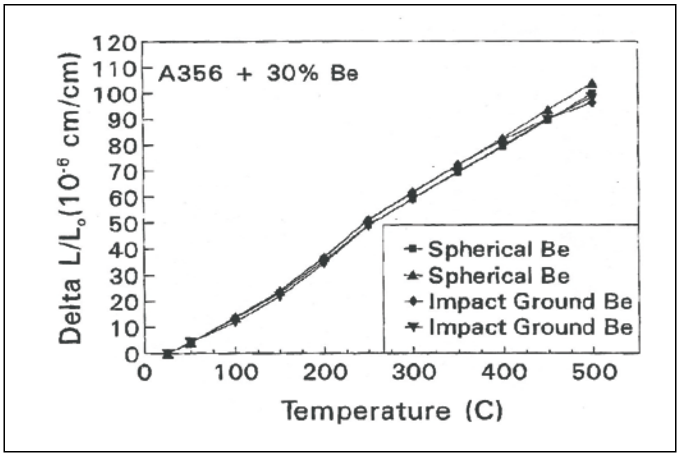


Figure 7. Delta L/L versus Temperature for SSM Formed AlBeMet® with 30% Impact Ground Beryllium.

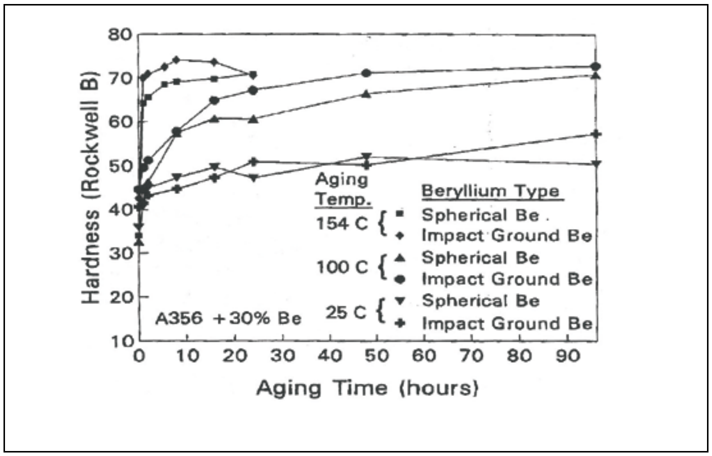


Figure 8. Aging Response of A356 + 30% Beryllium at 154°C (310°F), 100°C (212°F), and 25°C (77°F).

MECHANICAL PROPERTIES

Tensile Properties. Tensile properties were measured at room temperature on specimens from each of the unique combinations of injection speed, forming temperature, and preform extrusion reduction ratio. All specimens were tested in the as-SSM formed condition. The ultimate strength ranged from 43.1 ksi to 52.2 ksi. The data show a slight increase in strength with increasing forming speed. Yield strength values ranged from 25.5 ksi to 30.1 ksi. The data also show a slight increase in yield strength with increasing forming speed. Elongation values ranged from 3.0% to 8.0%.

Heat Treatment Response. The response of SSM processed A356 + 30% Be to heat treatments and aging conditions was evaluated using hardness measurements. The hardnesses reported are the average of at least 3 measurements. Both spherical and impact ground beryllium were evaluated. Hardness was also measured in the as-SSM formed condition. Solution heat treatment was performed at 538°C (1000°F) and quenched directly in water at 82°C (180°F). The aging treatments were performed on solution heat treated parts at either 154°C (310°F), 100°C (212°F), or room temperature. The aging times ranged from 1 hour to 96 hours.

The aging response curves are presented in Figure 8. For aging at 154°C (310°F), the peak aging time occurs at about 8 hours. The peak aging time at the other two temperatures occurred at about 96 hours, however, the peak hardness at room temperature aging is considerably lower than that achieved at 100°C (212°F) or 154°C (310°F).

METALLOGRAPHY

Metallographic examination of the broken tensile specimens shows that the distribution of beryllium is very uniform. An example of the microstructure obtained with this process is shown in Figure 9.

7075 and 6061 Aluminum Matrix Materials. A limited amount of work has been performed using both 7075 and 6061 as the aluminum matrix material. Approximately 30 connector caps were produced using 7075 with an average density of 2.424 g/cc ± .001 (99.9% ± 0.1% of theoretical density). Approximately 20 connector caps were produced using 6061 with an average density of 2.371 g/cc ± .005 (99.9 % ± 0.1% of theoretical density).

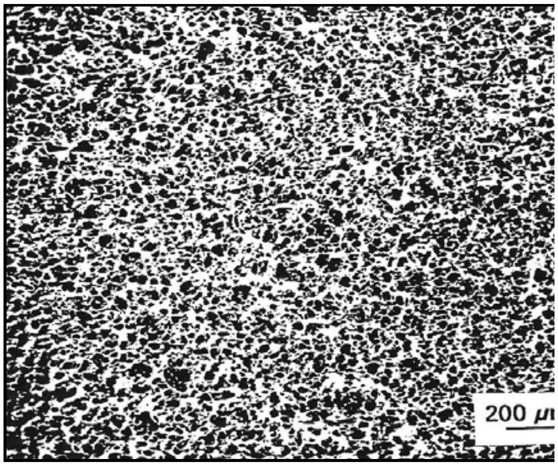


Figure 9. Typical Microstructure of SSM Formed Part – A356 + 30% Beryllium

The response of SSM processed 7075 and 6061 connector caps containing 30% Be to heat treatments and aging conditions was evaluated using hardness measurements. The hardnesses reported are the average of at least 4 measurements each on 3 different specimens. Hardness was also measured in the as-SSM formed condition. The solution heat treat temperatures were 470°C (878°F) and 529°C (985°F) respectively for 7075 and 6061. The aging temperatures were 121°C (250°F) and 177°C (350°F) respectively for 7075 and 6061. The aging response is shown in Figure 10. The hardnesses in the SSM formed condition were 80 (Rockwell B) and 56 (Rockwell B) respectively for 7075 And 6061. The solution heat treat temperatures were 470°C (878°F) and 529°C (985°F) respectively for 7075 and 6061. The aging temperatures were 121°C (250°F) and 177°C (350°F) respectively for 7075 and 6061. The aging response is shown in Figure 10. The hardnesses in the SSM formed condition were 80 (Rockwell B) and 56 (Rockwell B) respectively for 7075 and 6061.

Approximately 20 flange parts have been successfully fabricated using 7075 and 6061 as the matrix material (30% beryllium content). The average density of the flange parts was 2.415 g/cc ± 0.004 (99.55% ± 0.16% of theoretical density) for 7075 and 2.364 g/cc 0.004 (99.62% ± 0.17% of theoretical density) for 6061.

Approximately 20 Sabot parts have been successfully fabricated using 7075 and 6061 as the matrix material (30% beryllium content). The average density of the Sabot parts was 2.418 g/cc ± 0.004 (99.67% ± 0.16% of theoretical density) for 7075 and 2.374 g/cc ± 0.004 (100% ± 0.13% of theoretical density) for 6061.

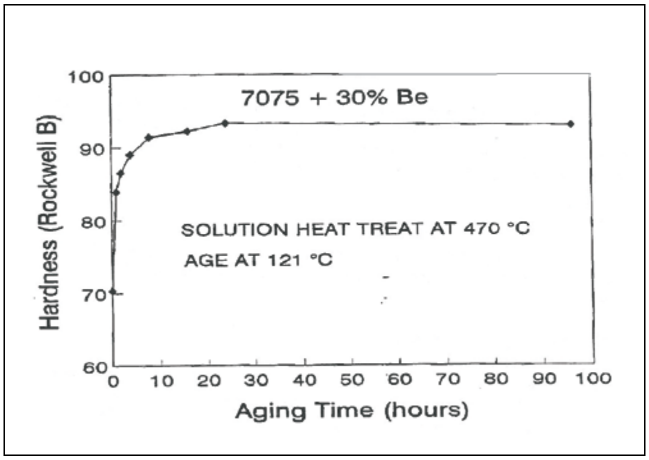
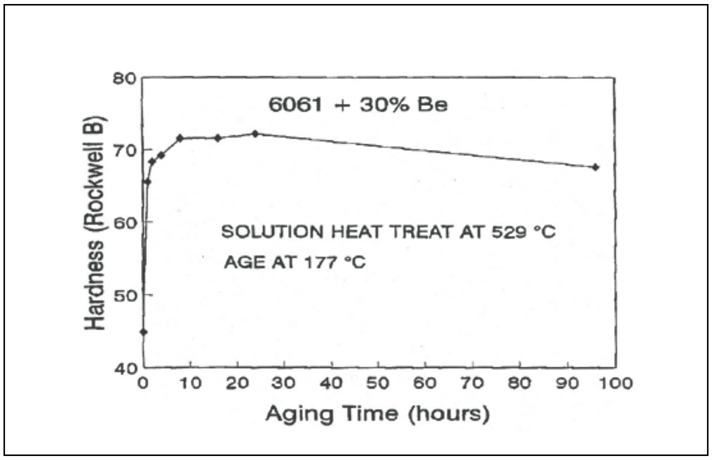


Figure 10. Aging Response at T6 Conditions (a) 7075 + 30% Beryllium



Aging Response at T6 Conditions (b) 6061 + 30% Beryllium

1) Semi-Solid Metal (SSM) processing has been successfully adapted to the AlBeMet® Metal Matrix Composites system. This adaptation involves the powder processing of the two materials (A356 and Be) into a preform which can be subsequently SSM processed without melting the Be Metal Matrix Composites component.
2) This process has also been successfully adapted-to the AlBeMet® Metal Matrix Composites systems using both 7075 and 6061 as the aluminum Metal Matrix Composites matrix material.
3) SSM properties match the rule of mixtures predictions based upon A356 (or 7075 or 6061) and Be. These properties also match properties of AlBeMet® processed using traditional technologies.
4) All three aluminum beryllium Metal Matrix Composites (A356 + 30% Be, 7075 + 30% Be, and 7075 + 30% Be) responded to the aging heat treatments in a manner similar to the pure aluminum Metal Matrix Composites.

5) The SSM process is cost effective in large volume applications with a complex three-dimensional shape. SSM offers lower input material cost and lower machining cost to produce the final part.
6) SSM allows for lower processing temperatures resulting in higher die life than conventional die casting techniques.

FUTURE WORK

Future work includes completion of the modulus testing and evaluation of the effect of heat treatment on tensile properties in A356. Evaluation of the pilot plant production of 1400 Sabots and evaluation of the effect of aging on parts produced from 7075 and 6061 are also planned.

REFERENCES

J. M. Marder, "Beryllium in Stress Critical Environments", Journal of Materials for Energy Systems, Vol. 8, No. 1, 1986, pp. 17-26.
R. J. Duba et al., "YF-12 Lockalloy Ventral Fin Program Final Report", 1976, Report NASA CR-144972.
E. W. Gossett Jr. et al., "Evaluation of Hot Isostatic Pressed Beryllium for Low Scatter Cryogenic Optics", Space Optical Materials and Space Qualification of Optics, Proceedings of SPIE 1118, 1989, pp. 50-58.
H. Okamoto and L. Tanner, eds., Phase Diagrams of Binary Beryllium Alloys, ASM International, Materials Park, Ohio, 1987, pp. 9-14.
D. Lewis, D Yaney, and L. Tanner, "Aluminum--Lithium--Beryllium Alloys", Aluminum--Lithium Alloys Vol. II, Materials and Component Engineering Publications Ltd., 1989, pp. 731-740. _
H. D. Hanes and A. J. Stonehouse, "HIP Beryllium Achieves Full Commercial Status", Metal Powder Report, Vol. 42, No. 10, 1987, pp. 708-711.
D. H. Hashiguchi, T. P. Clement, and J. M. Marder, "Properties of Beryllium Consolidated by Several Near-Net-Shape Processes", Modern Developments in Powder Metallurgy, MPIF/APMI, Vol. 18, 1988, pp. 627-643.
M. P. Kenney et al., "Semi-Solid Metal Casting and Forging", Metals Handbook Ninth Edition: Volume 15 - Casting, (ASM International, Materials Park, Ohio, 1988, pp. 327-338.
R. Mehrabian and M. C. Flemings, "Die Castings of Partially Solidified Alloys", Transactions of the American Foundryman's Society, Vol. 80, 1972, pp. 173-192.

Note: Handling Aluminum-Beryllium Metal Matrix Composites 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 Metal Matrix Composites, contact Materion.