Applications of an Aluminum-Beryllium Composite for Structural Aerospace Components

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Abstract

The use of AlBeMet AM162, an aluminum-beryllium metal matrix composite, is an effective way to reduce the size and weight of many structural aerospace components that are currently made out of aluminum and titanium alloys. These savings, which are essential for today's technologies, are primarily due to the material's high modulus and low density combined with its better than average specific strength. The raw material costs are significantly higher than they are for traditional engineering alloys, and the available billet sizes are more limited than they are for aluminum and titanium alloys. Although the material costs are higher for the aluminum-beryllium composite, ease of machining makes it financially competitive when compared to equivalent parts made out of titanium alloys. Due to toxic nature of beryllium, however, debris-generating operations must be strictly regulated to limit worker's exposure to the material and protect them from potentially fatal diseases.

Keywords: Metal matrix; AlBeMet; High elastic modulus; Low density; Weight reduction; Stiffness-driven design

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1. Introduction

The aerospace industry is continually searching for ways to reduce the weight of its products and maximize the amount of profit-making payload in launch vehicles. One of the most common ways engineers reduce weight is to make their products out of low-density alloys or engineering composites. These materials offer very high strength and/or stiffness to weight ratios; therefore, they require less mass and take less space to support a given load in comparison to other material choices. They have been the standard in the aerospace industry for decades and have a successful track record in a variety of applications. To keep up with technology advancements, however, additional high performance materials need to be investigated for use in space.

Some materials that have seen increased aerospace use in recent years are the family of aluminum-beryllium composites, which are available from Brush Wellman Inc. The most common composition of AlBeMet has the designation AM162 and contains 62% beryllium and 38% aluminum by weight (Marder). This material has a specific modulus that outperforms traditional aerospace alloys, making it an excellent candidate to reduce weight and dramatically increase the performance of stiffness-driven components. Besides its low density and high modulus, AlBeMet AM162 has additional properties that make it well suited for aerospace applications.

2. Material Properties

AlBeMet AM162 is a metal matrix composite (MMC) that is created by a gas atomized powder metallurgy process. The Al-Be powder is then cold isostatically pressed (CIP) to approximately 80% of its final density value before being extruded or rolled into its final shape and density (Marder). Finally, the material is annealed to relieve stress and is available in rod, bar, tube and sheet form (Ryczek). Although other forms are offered, this paper will primarily focus on the extruded and rolled shapes of AlBeMet AM162, for they offer the most benefit for strength critical designs and have the most data available.

The material properties for extruded and rolled forms of the Al-Be composite are essentially identical and are summarized in Table 2.1. For comparison, properties for the following commonly used engineering alloys are also shown: extruded 6061 aluminum with a T6 temper, extruded 7075 aluminum with a T73 temper, and titanium 6Al-4V in the annealed condition. The strength values shown are for the transverse direction and all the material properties assume a room temperature environment. The information was compiled from the following sources: Mil-Handbook-5G, Cambridge CES material selection software, actual material test data (Grensing), and vendor supplied data (Brush), which are coded a, b, c, and d, respectively. Averages were used for sources that cited a range of values for a particular material property.

Table 2.1: Material Properties for AlBeMet and Various Engineering Alloys

Material Property	**AlBeMet AM162**	**Aluminum 6061 T6**	**Aluminum 7075 T73**	**Titanium 6Al-4V**
Density, ρ (lb/in^3)	0.076^c	0.098^a	0.101^a	0.160^a
Ultimate Tensile Strength, σ_{tu} (ksi)	49^c	33^a	56^a	130^a
Yield Tensile Strength, σ_{ty} (ksi)	41^c	28^a	44^a	120^a
Ultimate Shear Strength, τ_u (ksi)	35^c	19^a	35^a	79^a
Ultimate Bearing Strength (e/D=1.5), σ_{bru} (ksi)	48^c	52^a	91^a	206^a
Endurance Limit, σ_e (ksi)	24^c	14^b	23^b	80^b
Modulus of Elasticity, E (Msi)	29^c	10^a	10^a	16^a
Shear Modulus, G (Msi)	14^b	4^a	4^a	6^a
Fracture Toughness (LT), K_{Ic} (ksi-in$^{1/2}$)	22^c	32^b	42^b	97^b
Elongation (Longitudinal), e (%)	10^c	10^a	7^a	10^a
Poisson's Ratio, μ	0.17^c	0.33^a	0.33^a	0.31^a
Melting Point, T_m (°F)	1980^d	1138^b	1025^b	2970^b
CTE, α (μin/in-°F)	7.7^c	12.9^b	13^b	4.9^b
Thermal Conductivity, λ (BTU/hr-ft-°F)	139.0^c	92.8^b	93.8^b	4.2^b
Specific Heat Capacity, C_p (BTU/lb-°F)	0.39^c	0.21^b	0.22^b	0.13^b

As Table 2.1 shows, AlBeMet has several properties that are particularly appealing for aerospace applications. In addition to the stiffness and weight advantages mentioned earlier, the thermal characteristics are perfect for the harsh space environment. With a high thermal conductivity and a high specific heat capacity, AlBeMet will serve as an excellent material for heat sinks, radiators, etc. Additionally, its relatively low CTE and high melting point will provide geometric stability over a fairly broad temperature range, which is essential for accurately aligned antennas or optical systems. If used to replace aluminum, the lower coefficient of thermal expansion will increase the performance of adhesively bonded metallic-graphite joints by minimizing the CTE mismatch, a critical failure area for many designs that are subjected to extreme temperatures. The following section will investigate the strength and stiffness characteristics of AlBeMet in detail.

3. Performance Indices

One way to rank different materials for various design criteria is to use performance indices (Ashby). With this method, a specific performance index is derived for given load conditions, member types, and free variable choices. The index is entirely composed of material properties and is usually a ratio of two variables. To evaluate the relative performance of each candidate material, simply input the specified properties into the index and calculate values for the various materials being considered. Higher values represent better performance for the selected design constraints.

Table 3.1 summarizes the performance indices for designs that are stiffness-driven. AlBeMet AM162 and several commonly used engineering alloys were evaluated using the material properties shown on Table 2.1 in the previous section. For ease of comparison, the values have been normalized by dividing by the lowest performer in each scenario.

Table 3.1: Normalized Performance Indices for Stiffness-Driven Designs

Member Type	**Cross-Section**	**Free Variable**	**Performance Index**	**AlBeMet AM162**	**Aluminum 6061 T6**	**Aluminum 7075 T73**	**Titanium 6Al-4V**
Tie	Round	Area	E/ρ	**3.9**	1.0	1.0	1.0
Beam	Rectangular	Width					
Shaft	Round Tube	Thickness	G/ρ	**5.0**			
Column	Round	Area	$E^{1/2}/\rho$	**2.8**	1.3	1.2	1.0
Beam	Square	Area					
Shaft	Round Tube	Area	$G^{1/2}/\rho$	**3.2**			
Plate	Rectangular	Thickness	$E^{1/3}/\rho$	**2.6**	1.4	1.3	1.0
Beam	Rectangular	Height					
Shaft	Round Tube	Radius	$G^{1/3}/\rho$	**2.8**			

As expected, the aluminum-beryllium composite is the best performer for stiffness designs due to its combination of high elastic modulus and low density. The data indicates that a tie (tension member) made of AlBeMet would be 3.9 times stiffer than an equivalent weight member made of aluminum or titanium, given the freedom to vary the cross-sectional area. Conversely, if equivalent stiffness' were compared, the AlBeMet tension member would be 3.9 times lighter than the other materials. Because many aerospace applications are stiffness driven, this appears to be a valuable way to reduce weight. Due to AlBeMet's lower strength values, however, reductions of this magnitude may not be possible because strength may become the limiting design constraint. To see how its strength ranks in comparison to the traditional aerospace alloys, performance indices for this scenario need to be generated.

Using the same process described previously, the no-yield performance indices for several types of strength-driven members were generated and appear in Table 3.2 where they have been evaluated for AlBeMet and a few common engineering alloys. Once again, the values have been normalized by dividing by the lowest performer in each row.

Table 3.2: Normalized Performance Indices for Strength-Driven Designs

Member Type	**Cross-Section**	**Free Variable**	**Performance Index**	**AlBeMet AM162**	**Aluminum 6061 T6**	**Aluminum 7075 T73**	**Titanium 6Al-4V**
Tie	Round	Area	σ_{ty}/ρ	1.9	1.0	1.5	**2.6**
Column	Round	Area					
Beam	Rectangular	Width					
Shaft	Round Tube	Thickness					
Beam	Square	Area	$\sigma_{ty}^{2/3}/\rho$	**1.7**	1.0	1.3	1.6
Shaft	Round Tube	Area					
Beam	Rectangular	Height	$\sigma_{ty}^{1/2}/\rho$	**1.6**	1.0	1.2	1.3
Plate	Rectangular	Thickness					
Shaft	Round Tube	Radius					

Table 3.2 uncovered a surprising discovery. AlBeMet actually exceeds the performance of titanium in certain scenarios. If the member is a beam, a plate, or a shaft, and the free variables are the height, the thickness, and the radius, respectively, AlBeMet out performs titanium by nearly 25%. This was unexpected because the yield strength for titanium is approximately 3 times greater than that of the Al-Be composite. The explanation for this is quite simple, however. For all three cases, the free variable is the geometric parameter that most efficiently reduces the stress in the member. In the case of the rectangular beam for example, the bending stress is given by the expression:

$$\sigma = \frac{Mc}{I} = \frac{M\left(\frac{h}{2}\right)}{\left(\frac{wh^3}{12}\right)} = \frac{6M}{wh^2}$$

This causes the stress to decrease quadratically as the height h is increased. Because the beam's mass increases linearly as the height is extended, and the density of AlBeMet is significantly less than that of titanium, the lighter, weaker material quickly gains ground and outperforms the heavier, stronger alloy as the free variable increases. Despite titanium's superb strength characteristics, it is actually the third-most weight efficient choice for these applications: definitely not an intuitive notion. Given a different set of constraints, however, such as the ones in the top portion of Table 3.2, titanium has superior performance compared to the other materials and will produce the lightest, strongest members.

4. Material Availability and Cost

The drawbacks of using AlBeMet are the limited extrusion and rolled sheet sizes available and the excessive amount of time required for procuring the material. Table 4.1 summarizes the various configurations and lead-times available (Ryczek).

Table 4.1: Raw Material Sizes Available for AlBeMet AM162

<table>
<tr><th colspan="4">Extrusions</th></tr>
<tr><th colspan="2">Cross-Section</th><th>Length (in)</th><th>Lead-Time (weeks)</th></tr>
<tr><td colspan="2">Up to 3.00 inch diameter</td><td>48</td><td>6-8</td></tr>
<tr><td colspan="2">3.00-5.00 inch diameter</td><td>48</td><td>Consult Vendor</td></tr>
<tr><td colspan="2">Rectangle up to 8 sq. in.</td><td>48</td><td>6-8</td></tr>
<tr><td colspan="2">Rectangle up to 16 sq. in.</td><td>48</td><td>Consult Vendor</td></tr>
<tr><th colspan="4">Rolled Sheet</th></tr>
<tr><th>Thickness (in)</th><th>Width (in)</th><th>Length (in)</th><th>Lead-Time (weeks)</th></tr>
<tr><td>0.020</td><td>20</td><td>42</td><td>12-16</td></tr>
<tr><td>0.063</td><td>20</td><td>45</td><td>12-16</td></tr>
<tr><td>0.125</td><td>24</td><td>28</td><td>12-16</td></tr>
<tr><td>0.188</td><td>20</td><td>25</td><td>10-14</td></tr>
<tr><td>0.250</td><td>15</td><td>26</td><td>10-14</td></tr>
<tr><td>0.313</td><td>12</td><td>28</td><td>8-10</td></tr>
</table>

These offerings are significantly limited when compared with either aluminum or titanium alloys. These alloys are typically available up to 4 to 6 inches thick with widths and lengths of several feet (Neill). For many applications, however, the AlBeMet sizes shown above are more than adequate. The extra long procurement time will need to be factored in to the project's schedule to void costly delays, however. This precaution isn't generally needed for aluminum or titanium because they're readily available in these sizes, usually with 48 hours (Neill).

Another factor that may deter engineers from choosing the aluminum-beryllium composite for their designs is its relatively high material costs. Table 4.2 compares its cost with the average cost of commonly used engineering alloys (Cambridge). The prices are shown on a per pound basis as well as a per volume basis. Since the material densities vary so greatly, and raw billets for machined parts are usually purchased based on the finished product's overall dimensions, a volume price comparison is the most appropriate cost measurement.

Table 4.2: Raw Material Cost Comparison for AlBeMet and Various Engineering Alloys

	AlBeMet AM162	**Aluminum 6061 & 7075**	**Titanium 6Al-4V**
Average Cost/lb ($)	407.80	0.65	13.23
Average Cost/in^3 ($)	30.99	0.07	2.12

As the table indicates, a billet of AlBeMet AM162 is over 400 times more expensive than an equivalently sized piece of aluminum. For large parts, which require large billets, this appears to be an unrealistic option. Even though the AlBeMet composite offers greater performance in many applications, the high cost increase would be difficult to justify. When comparing its price to titanium, however, the difference is much more palatable at 15 to 1. Given the difficulties associated with machining titanium, which are addressed in a later section, the performance advantages and weight savings offered by AlBeMet are definitely worth investigating.

5. Health and Safety Concerns

The biggest disadvantage of using an Al-Be composite is the serious health concerns related to beryllium. The greatest danger is inhaling beryllium dust, which can lead to chronic beryllium disease (CBD), a disabling lung illness that has no cure and is often fatal. The symptoms of CBD are persistent coughing, difficulty breathing, fatigue, chest and joint pain, weight loss, and fevers. These symptoms, which can take up to 30 years to appear, are caused by an allergic reaction between the body's immune system and the metal. Additionally, skin disease can be caused by direct contact with fine beryllium particles. Approximately 2 to 10% of workers exposed to beryllium have contracted these illnesses (OSHA). The current OSHA standard regarding the exposure limit for beryllium in the workplace is 2 micrograms per cubic meter of air over an eight-hour time-weighted average. Due to a lack of data regarding the long-term effects of beryllium exposure, OSHA is concerned that the current limit is inadequate and may not prevent CBD. Because of this, many companies that use beryllium alloy finished goods forbid any debris generating operations on these parts once they've been received from the supplier. This may pose a problem for hardware that needs to reworked, repaired, or altered intentionally during installation at the next higher assembly. Company policy may mandate that this work be performed back at the supplier or at another authorized vendor. This can cause schedule delays and logistics issues, especially for large assemblies or for hardware that is proprietary in nature. It is important to note that there are currently no health concerns regarding the handling of properly cleaned beryllium components.

6. Machinability

As mentioned previously, there are significant health concerns regarding the inhalation of beryllium dust. For this reason, additional steps must be taken when machining AlBeMet. Ventilation systems are required during machining operations and extra care should be taken when handling uncleaned finished parts or chips created during the fabrication process. These items may have fine particles of beryllium on them and should be cleaned under a fume hood while wearing gloves and a respirator. Debris should be disposed of per local environmental requirements or recycled and sent back to Brush Wellman.

In addition to the extra set-up and handling time, actual machining time for AlBeMet is longer than it is for equivalent aluminum alloy parts. The material can be cut with standard carbide cutters but requires 15-20% slower speeds and feeds as compared to aluminum alloys (Ryczek). Combining the set-up and machining time, an aluminum-beryllium part will take roughly 25% longer to fabricate than its aluminum alloy counterpart. This extra time directly translates into increased costs for the final product. For perspective, however, a titanium part takes approximately 3 times longer to machine than the same part made of aluminum (Neill). Again, the increased machine time is directly proportional to the cost of fabricating the part. Table 6.1 summarizes the cost factors associated with machining the three types of materials.

Table 6.1: Cost Factor for Machining AlBeMet and Various Engineering Alloys

	AlBeMet AM162	**Aluminum 6061 & 7075**	**Titanium 6Al-4V**
Average Cost Factor (relative to aluminum)	1.25	1	3
Average Cost Factor (relative to AlBeMet)	1	0.8	2.4

Although the material costs for AlBeMet are higher than they are for titanium, the machining costs are much less. As the table indicates, titanium is approximately 2.4 times more expensive to machine. Depending on the size and complexity of the finished part, it may actually be cheaper to fabricate it out of AlBeMet since the total cost to fabricate the part is the sum of the machining and material costs. Using the machining cost for AlBeMet as the baseline, and by applying the raw material cost data from Table 4.2, the following equations were generated to estimate the total cost for parts of equal complexity made from either titanium or AlBeMet:

$$(Total\ Cost)_{Ti} = 2.4 \times (Machining\ Cost)_{Al-Be} + (\$2.12 / in^3)(Billet\ Volume)_{Ti} \tag{6.1}$$

$$(Total\ Cost)_{Al-Be} = (Machining\ Cost)_{Al-Be} + (\$30.99 / in^3)(Billet\ Volume)_{Al-Be} \tag{6.2}$$

To determine the financial breakeven point for parts of equivalent complexity and size, the total costs defined by equations 6.1 and 6.2 were equated to one another. The following expression relates the part's complexity to the corresponding billet size that satisfy this cost constraint:

$$(Machining\ Cost)_{Al-Be} = \frac{(\$30.99/in^3 - \$2.12/in^3)\times(Billet\ Volume)_{Eq}}{(2.4-1)} = (\$20.62/in^3)\times(Billet\ Volume)_{Eq} \tag{6.3}$$

Using Equation 6.3, a large range of machining costs, which represent various levels of finished part complexity, were calculated for a variety of raw material billet sizes and the results are shown on Figure 6.1 below. To use the figure to determine which material is less expensive for a given part, use a machining cost and billet size estimate to generate a point on the graph. If the point lies above the line, it is less costly to choose AlBeMet. This indicates that the part is manufacturing intensive and relatively small so its price is driven by machining time, rather than material costs. Conversely, if the point lies below the line it is in the titanium region. For this case, the costs are driven by the large amount of material required, not the part's complexity. In this scenario, titanium is the financially sound choice. To generate titanium part estimates, the machining costs for that material were added to the figure by scaling them appropriately.

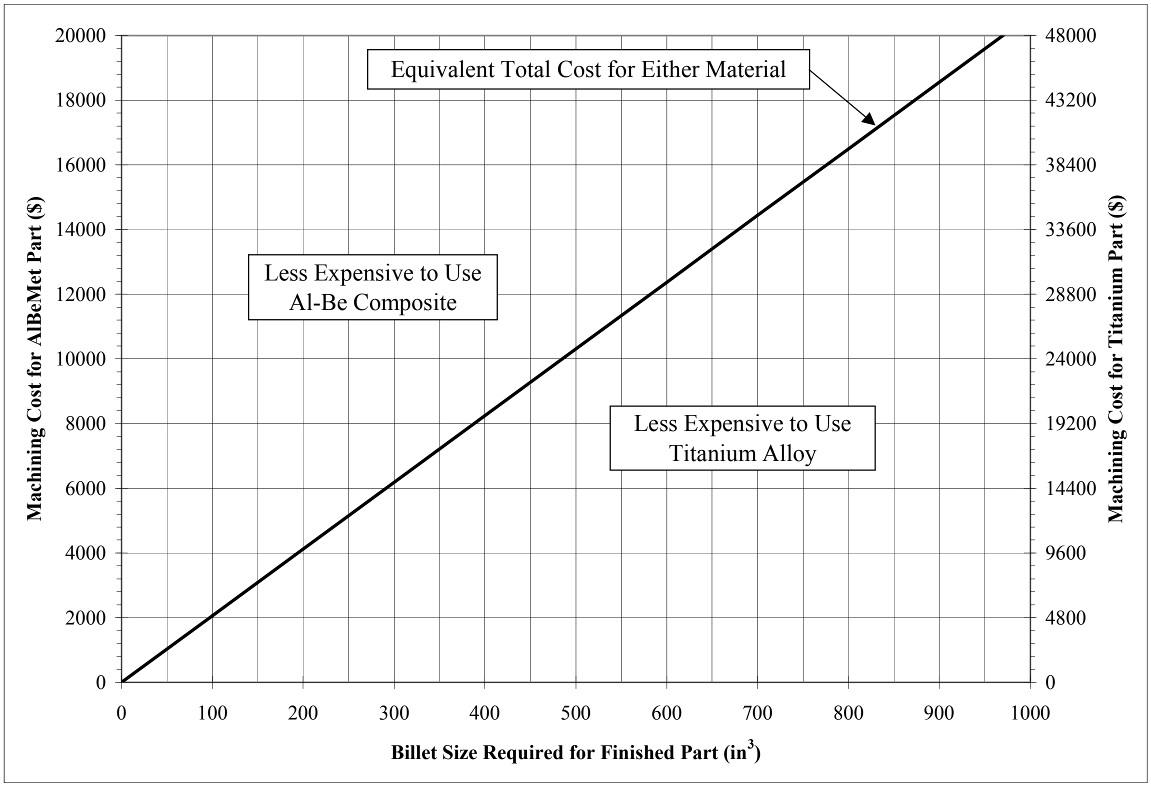

Figure 6.1: Equivalent Cost for Titanium or AlBeMet Parts for Various Billet Sizes

7. Conclusion

AlBeMet's extremely high specific stiffness combined with its above average strength-to-weight ratio makes it an ideal material to increase the performance of weight critical aerospace structural components. In addition to reducing weight, space savings are possible for stiffness-driven structure designs due to the material's high modulus of elasticity. Besides its attractive mechanical properties, AlBeMet's thermal properties are a perfect match for the extreme temperatures of space. Its low CTE, high melting point, high thermal conductivity, and high specific heat capacity are all favorable traits for a variety of aerospace applications.

As far as cost, aluminum-beryllium composite parts will always be more expensive than equivalent aluminum alloy parts. The cost increase would be difficult to justify unless the performance requirements demanded the pricier material. Any money saved due to lower launch costs would likely be consumed in the manufacturing of the AlBeMet parts. When used to replace titanium components, however, the Al-Be composite can provide improved performance for a lower cost. Despite the high material cost of AlBeMet, its relative ease to machine makes it a better choice financially in many cases, especially for components with complicated geometry.

The main disadvantage of using AlBeMet for structural components is the serious health risks associated with machining beryllium. Parts can only be made or altered in a controlled and monitored area. This can be a problem for hardware that needs to drilled or reworked at the assembly level. Additional drawbacks are the size limits of the material and the long lead-times for procurement. These factors must be accounted for early in the design phase when evaluating the various material candidates for each component.

If the health concerns are properly addressed, Al-Be composites can safely be used to replace traditional engineering alloys in a variety of aerospace structural applications. High-performance materials like AlBeMet AM162 are essential for engineers who are trying to solve the challenges of designing more powerful and efficient payloads while minimizing launch costs.

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