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Plasma Transferred Arc Deposition of Beryllium

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The exceptional properties of beryllium (Be), including low density and high elastic modulus, make it the material of choice in many defense and aerospace applications. However, health hazards associated with Be material handling limit the applications that are suited for its use. Innovative solutions that enable continued use of Be in critical applications while addressing worker health concerns are highly desirable. Plasma transferred arc solid free-form fabrication is being evaluated as a Be fabrication technique for civilian and military space-based components. Initial experiments producing Be deposits are reported here. Deposit shape, microstructure, and mechanical properties are reported.

Keywords beryllium (Be), plasma transferred arc, structural material, tensile strength, wetting

1. Introduction

1.1 Property Requirements

Space-based systems for civilian and military applications require extremely lightweight and stiff materials that can survive the harsh conditions of launch and space environmental exposures. In addition, material and fabrication costs must fall within budget for the implementation to be feasible. The primary requirements for space-based structural components are:

- *Weight*: The components must be ultra lightweight to reduce launch costs.
- *Deformation resistance*: To maintain shape throughout all phases of handling, testing, launch, and deployment, very high resistance to deformation is required.
- *Fabrication dimensional accuracy*: The as-fabricated dimensional accuracy must fall within requirements determined by the mission.
- *Cost*: The cost of materials, fabrication, and testing must be compatible with the funding allocations for specific missions.
- *Health risk*: The risk to workers fabricating, assembling, and testing components must be as low as possible.

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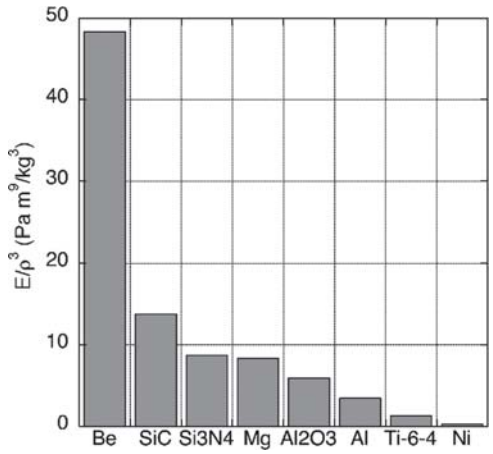

Fig. 1 Material comparison for cylindrical figure of merit for space structures

1.2 Material Comparison

For a constant weight cylinder, the deformation due to an imposed load varies according to the density cubed divided by the elastic modulus. The figure of merit used for deformation resistance is therefore the elastic modulus divided by the density cubed (E/ρ^3) (Ref 1). The advantage of using beryllium (Be) over other proposed materials is evident when considering the figure of merit for deformation as shown in Fig. 1. Since the density of Be is low (1848 kg/m^3) and the elastic modulus is high (303 GPa), the E/ρ^3 value for Be is the largest known for any structural material.

1.3 Proposed Technology

To produce components at the lowest cost with minimal worker exposure to fine particulate Be, near-net-shape technologies that reduce the need for machining are attractive. Near-net-shape casting, however, has severe limitations. Beryllium has a high latent heat of fusion, a relatively high melting point (for a low atomic weight metal), and low thermal conductivity. These

factors combine to cause the formation of large columnar grains (in the direction of heat flow) in cast material. This grain structure limits the mechanical properties of cast Be to ultimate tensile stress values of 34 to 68 MPa and nil ductility (Ref 2). To control the grain size and improve mechanical properties, Be is typically processed by making a powder, consolidating it by vacuum hot pressing, and machining parts from the hot-pressed log. However, large, thin-walled structures made in this way produce large amounts of material waste. This increases cost, and, since the machine chips are a hazardous form of Be particulate, hazardous exposure to workers increases also. Another existing Be near-net-shape fabrication technique is hot isostatic pressing of powder. However, this technique requires single-use, complex tooling in the form of powder containment cans to produce near-net-shape complex parts. The ideal solution is a near-net-shape fabrication technique that minimizes cost and health risk, delivers the superior mechanical properties of powder-processed Be, and does not require complex, single-use tooling.

Solid free-form fabrication (SFF) is an additive manufacturing technique that produces three-dimensional (3D) objects by moving a deposition source along a prescribed 3D path to stack layers of material in succession. The path of the deposition can be varied in successive passes to form complex geometry parts requiring only finish machining. In plasma transferred arc (PTA) deposition, powder is injected into a weld pool created by a focused arc to build up a deposit layer. PTA SFF is the use of PTA deposition to produce near-net-shape, 3D parts (Ref 3). Producing Be parts by PTA SFF would reduce the required machining compared with the traditional vacuum hot pressing route. By performing PTA SFF of Be in a chamber, the operator is isolated from the Be particulate. Therefore, PTA SFF of Be offers the potential for near-net-shape fabrication of Be components at low cost and low worker health risk. However, to the authors' knowledge, PTA deposition of Be has never been demonstrated. Therefore, the mechanical properties of PTA Be are unknown and must be evaluated to assess their suitability for space-based applications. The study described here investigates the PTA deposition of Be and evaluates the microstructure and tensile properties of the deposit.

2. Experimental Procedure

2.1 Deposition Conditions

Beryllium was deposited by PTA deposition. The PTA torch used was a Eutectic model 220 (Castolin Eutectic Group, Kriftel, Germany) used with an extended anode/nozzle and 2.3 mm diameter tungsten cathode. The powder was metered using a Praxair (Praxair-TAFA, Concord, NH) model 1264 powder hopper. Argon (99.999% minimum purity) was used as the arc gas, shield gas, and powder carrier gas. The arc gas flow rate was 2 L/min, shield gas flow was 7 L/min, and powder gas flow was 2 L/min. The torch current was 45 A. Alternating current (ac) at 60 Hz was used for both cathodic arc cleaning on the substrate/deposit and efficient melting of the deposit while minimizing heating of the torch tungsten electrode. The torch was oscillated 10 mm back and forth across the deposit area. The Be was deposited on a 304 stainless steel tube with an outside diameter of 50.8 mm and a wall thickness of 2.9 mm. The tube was mounted in a rotating fixture and turned at 0.3 rpm. Deposition took place in a vacuum chamber that was pumped down and backfilled with argon to atmospheric pressure before deposition. Oxygen levels were maintained below 5 ppm for all deposited material as indicated on a trace oxygen analyzer (Alpha Omega Instruments Series 3000, Cumberland, RI).

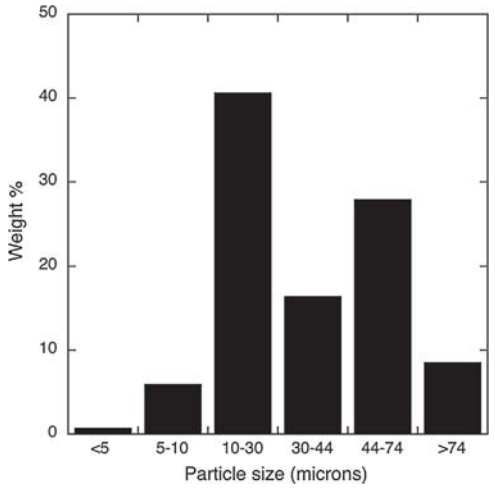

Fig. 2 Powder size distribution of Be powder determined by sieve analysis

2.2 Powder

Powder size for PTA deposition is typically in the 50 to 150 μm range. However, commercial Be powder is not available in this size range. Therefore, commercially available gas atomized O-30 Be powder (Brush Wellman, Inc., Cleveland, OH) was used because of its spherical shape and relatively free-flowing characteristics. This powder had a size distribution of −80 +5 μm as shown in the sieve analysis in Fig. 2. Figure 3 shows the spherical shape of the powder in an SEM image. The chemical composition of the powder is given in Table 1 as measured by Brush Wellman Inc., the manufacturer.

2.3 Characterization

The deposited material was characterized by caliper measurements to determine the height and width of the deposits. Deposits were also cut, ground, and polished for optical microscopy. Two tensile test samples were machined and pulled to determine mechanical properties. The tensile test samples were 1.5 mm gage diameter with a gage length of 7.5 mm. The samples were pulled at a crosshead velocity of 0.002 mm/s, which gave a strain rate of 2.7×10^{-4}/s.

3. Results and Discussion

3.1 Beryllium Microstructure

The Be sample deposited by PTA was 10 mm wide and 6 mm high. The Be deposit was sectioned and polished to reveal the microstructure. Figure 4 shows the microstructure in the center and top of the deposit. Figure 5 shows a higher-magnification

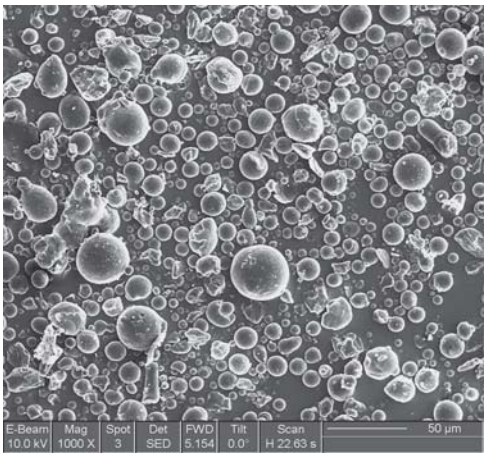

Fig. 3 SEM image of the Be powder used for PTA deposition. Note: the powder was taken from the side wall of a container and is not an average sample of particle size.

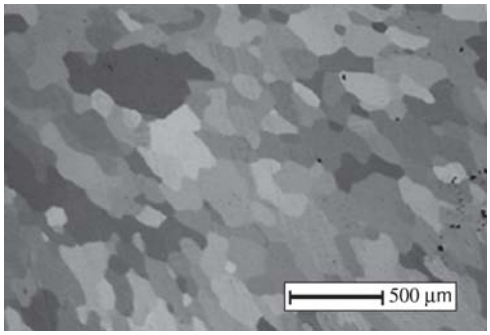

Fig. 4 Cross section of Be deposit

Table 1 Beryllium powder chemical composition

Element/material	Composition
BeO, wt.%	0.64
C, wt.%	0.086
Fe, ppm	1090
Al, ppm	425
Si, ppm	325
Be	bal

view of the structure near the top of the deposit. Small amounts of porosity are visible in each figure. This porosity is similar to that observed in castings and has been attributed to gas or vapor evolution during solidification (Ref 4). Grain size in the deposit ranged from 50 to 750 µm in diameter with an average of approximately 250 µm. Grain shapes also vary in Fig. 4 with the grains at the top of the image showing equiaxed shapes, while the grains near the bottom of the image showing elongated structures in the direction perpendicular to the substrate surface. Since the substrate temperature is cooler than the molten Be, heat is conducted out of the deposit in the direction of the substrate. This heat conduction direction coincides with the long dimension of the columnar grains near the substrate showing the effect of heat conduction on solidification. Farther away from the substrate, the heat flow is more evenly divided between traveling to the substrate and being transferred across the Be-free surface to the environment by means of conduction, convection, and radiation. This multidirectional heat flow results in more equiaxed grains. Since the Be cooling rate decreases as the distance from the substrate increases, smaller grains are seen in the center of the deposit with the larger grains at the top free surface of the deposit.

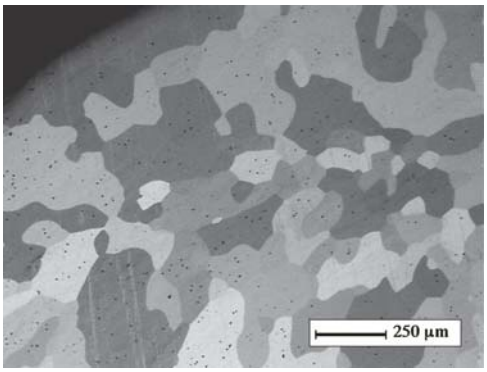

Fig. 5 Cross section of Be deposit at higher magnification

3.2 Tensile Test Results

Two miniature tensile test samples were machined from the as-deposited (no annealing treatment) PTA Be material. The engineering stress/strain plot from testing is shown in Fig. 6. The 0.2% offset yield stresses (YS) for the two samples were 189 ± 5 MPa and 175 ± 5 MPa, and the ultimate tensile stresses (UTS) for the samples were 229 ± 5 MPa and 191 ± 5 MPa. The strain at failure was 1.4 ± 0.1% for the first sample and 0.6 ± 0.1% for the second sample. For comparison, engineering stress/strain test results for a commercial hot-pressed Be material S200F (Brush Wellman, Cleveland, OH) with the same sample size and test conditions are also shown in Fig. 6. The YS for the hot-pressed Be is 221 ± 5 MPa, the UTS is 377 ± 5 MPa, and the strain at failure is 4.4 ± 0.1%. The hot-pressed material has a grain size of approximately 12 µm.

Compared with the hot-pressed Be sample, this initial PTA material has lower YS, UTS, and failure strain. In powder-processed Be, the mechanical properties are principally related to the grain size of the material and the material purity (Ref 5). The lower strength and lower failure strain of the PTA material are likely due to its larger grain size. Also contributing to the lower failure strain is the porosity observed in Fig. 4 and 5 that acts as stress concentration and crack initiation sites. The relationship between grain size and yield stress for steels was formulated by Hall (Ref 6) and Petch (Ref 7) and is known as the "Hall-Petch equation." For many metals, the Hall-Petch equation shows that the YS of a material is proportional to the inverse square root of the grain size. This is shown by:

$$\sigma_Y = \sigma_Y' + K_Y d^{-1/2} \quad \text{(Eq 1)}$$

where σ_Y is the YS, d is the grain size, and σ_Y' and K_Y are constants. The YS of powder-processed Be metal consolidated under a variety of techniques closely follows Eq 1 (Ref 5).

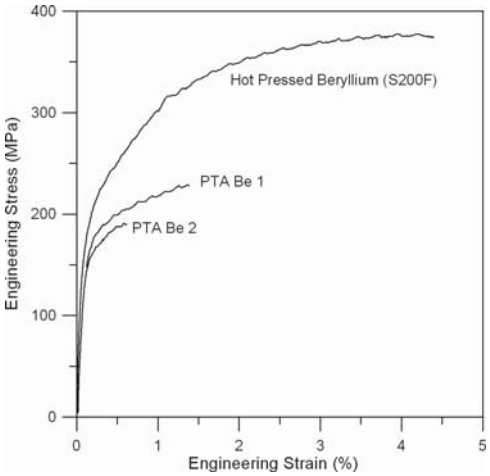

Fig. 6 Tensile stress/strain plot for the two PTA Be samples and one hot-pressed commercial Be sample

Fitting the data given in Ref 5 gives approximate values for the constants (with d in μm) as $\sigma_Y' = -34$ MPa and $K_Y = 938$ MPa · $\mu m^{1/2}$. Using a grain size of 12 μm for the hot-pressed S200F, Eq 1 predicts the YS to be 237 MPa, which is in close agreement to the measured value of 221 MPa. In a powder-processed material, Eq 1 predicts YS of 189 and 175 MPa from material with an average grain size of 18 and 20 μm, respectively. These predicted grain sizes are much smaller than the PTA material grain size of 250 μm.

The YS of PTA Be is not well predicted by the σ_Y' and K_Y constants given previously from powder-processed material data. Therefore, PTA and powder-processed materials differ in some significant way affecting tensile properties. Powder-processed metals typically have reaction product layers (oxides for Be metal) at the prior particle boundaries that affect the bonding between particles and subsequently the mechanical properties of the material. The reaction products at prior Be particle boundaries also limit grain growth during high-temperature processing (Ref 5). PTA material goes through melting in the final processing stage, and therefore the material from the feed powder outer surface is redistributed into the bulk of the deposit. Because impurities and their distribution are also known to affect mechanical properties of Be, it is likely that the redistribution from melting has led to different tensile YS for a given grain size. In a similar way, the porosity distributed throughout the PTA Be grains can pin dislocations, also increasing the YS of the PTA material.

Other factors that might contribute to the higher-than-expected strength of the PTA material are residual stress and texture. Thermal gradients in the deposit during deposition and cool down cause strain gradients that result in residual stress. This residual stress can exceed the yield point of the material leading to plastic deformation that increases the yield stress in a way similar to adding mechanical work. Because the powder-processed material is in an annealed condition, residual stresses could cause differences in the expected YS between the powder-processed and PTA materials. Single-crystal studies in Be have shown that the number of possible deformation mechanisms is very limited, and therefore the mechanical properties will be strongly influenced by preferred crystallographic orientation or texture (Ref 8). The directional solidification of the PTA deposit likely induces nonrandom texture in the material. Differences in texture between the PTA and powder-processed material may partially account for the unexpected mechanical test results described previously.

Considering the physical processes involved during fabrication, arc welded Be is expected to be much closer in character to PTA deposited Be than powder-processed material. Though little data exist, the mechanical properties of arc welded Be have been found to be a direct function of the material grain size (Ref 9). Room-temperature UTS of gas tungsten arc welded Be range from 259 MPa for 40 to 60 μm grain size weld material to 172 MPa for 80 μm grain size weld material (Ref 10). The tensile elongation of the arc welded Be is given as 0.2 to 1.6% in Ref 10. The corresponding values listed above for PTA Be with a grain size of 250 μm (UTS of 229 and 191 MPa) are similar to the values for arc welded Be with grain size in the range of 40 to 80 μm. As with the comparison to powder-processed Be, the PTA material has tensile strength that is higher than expected considering the large grain size. Impurity content and distribution along with differences in porosity, residual stress, and grain orientation are also expected to be the cause of the differences between arc welded and PTA deposited Be tensile strength.

The initial PTA Be material tested in this study achieves relatively high strength (compared with cast Be) with large grain size (compared with powder-processed Be). The strength makes PTA Be suitable for many current space-deployed structural applications. Furthermore, if process refinement can reduce the grain size of PTA Be, subsequent strength and ductility increases would make PTA Be suitable for an even broader range of space-based structural applications.

4. Conclusions

Conclusions that resulted from this investigation are:

- Plasma transferred arc deposition of Be metal has been demonstrated.
- The PTA Be deposit had small amounts of porosity present.
- The PTA Be deposit has grain sizes in the wide range of 50 to 750 μm.
- The tensile yield stresses (0.2% strain offset) of the PTA Be samples were 189 and 175 MPa and the ultimate tensile stresses were 229 and 191 MPa.
- The strains at fracture for the PTA Be samples were 1.4% and 0.6%.
- The mechanical properties of the initial PTA Be samples are reduced compared with optimized hot-pressed S200F Be.
- Considering the grain size effect on mechanical properties, the PTA Be strength compares favorably to that of hot-pressed and arc welded Be.
- PTA SFF Be offers potential improvements in cost and worker health risks over traditional powder-processed Be. The mechanical properties of PTA Be measured in this study are already suitable for many space-based structural applications. Further development of the PTA SFF tech-

nique to reduce deposit grain size and improve mechanical properties would make it suitable for an even broader range of space-based structural applications.

Acknowledgments

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