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AUTHOR(S): M. Hill, B.K. Damkroger, R. D. Dixon, E. Robertson

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Beryllium Weldability

AUTHOR(S) (upper and lower case)	AFFILIATION(S) (city & state) (upper and lower case)
1. Mary Ann Hill	1. Los Alamos National Laboratory Los Alamos, New Mexico
2. Brian K. Damkroger	2. Los Alamos National Laboratory Los Alamos, New Mexico
3. Raymond D. Dixon	3. Los Alamos National Laboratory Los Alamos, New Mexico
4. Erica Robertson	4. Air Force Office of Scientific Research Bolling AFB, Washington, DC
5.	5.

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ABSTRACT

Welding processes and metallurgical considerations for beryllium welding are discussed in this review. The primary difficulties of welding beryllium are hot cracking, cracking at defects, and ductility limitation or thermally induced cracking. Solutions to these welding problems include control of the Fe/Al ratio in the base metal to reduce hot cracking, minimization of the BeO content and starting grain size to limit cracking at defects and ductility limitation cracking, and optimization of the welding process and process variables.

I. INTRODUCTION

Beryllium exhibits a unique combination of low density, high specific strength and stiffness, and high specific heat and thermal conductivity. These characteristics make beryllium an attractive engineering material for a variety of applications. However, beryllium does have several noteable drawbacks including toxicity, low fracture toughness, and high cost. As a result, the application of beryllium has been somewhat limited. Aerospace applications include structural components on the space shuttle (1), military aircraft (2,3) and other space vehicles (4). Instrumentation applications of beryllium include gyroscopes, accelerometers, optical support benches, mirror substrates, inertial guidance instrument housings, and x-ray windows. The nuclear industry uses beryllium for fuel element cladding, moderators, and reflectors in compact high-flux atomic reactors and beryllium alloys for neutron sources (5).

The application of beryllium as a structural material in many cases involves welding. Beryllium has been successfully welded by several processes, including gas tungsten arc (GTA), gas metal arc (GMA), and electron beam (EB) welding (6-8). The primary and most severe restriction on the welding of beryllium is its crack sensitivity. The types of weld cracking that may be encountered include hot cracking due to an aluminum-rich grain boundary film, cracking originating at defects (oxide particles, voids, inclusions), and sub-solidus cracking due to its inherently low ductility. Although this cracking is affected by weld processes and parameters, it is largely controlled by the metallurgical characteristics of the beryllium itself.

This paper will review the fusion welding of beryllium. This will be done by considering individually the effects that several metallurgical factors and process variables have on the structure, properties, and cracking susceptibility of beryllium weldments.

II. BERYLLIUM CHARACTERISTICS

THERMOPHYSICAL PROPERTIES - Several thermophysical properties affect the weldability of a material. These include the coefficient of thermal expansion, thermal conductivity, specific heat, melting point, and density. The properties of beryllium are given in Table 1 (9-11). The thermal conductivity of beryllium is higher than most metals with the exception of copper and aluminum. The thermal diffusivity ($\lambda/\rho c$) for beryllium is also high. The thermal gradient is inversely proportional to the thermal diffusivity so the thermal gradient able to be sustained in beryllium is relatively low. However, the thermally induced stresses still play a significant role in weld cracking due to the low ductility of beryllium. Additionally, the anisotropy of the thermal conductivity (λ) and specific heat (C_p) of beryllium make it difficult to accurately control weld cooling rate and pool shape.

CRYSTALLOGRAPHY - Beryllium has a hexagonal close packed (hcp) structure and the smallest c/a ratio of all hcp elements, 1.568, as compared to the ideal c/a ratio of 1.633. There are only three primary slip systems in beryllium, basal, prismatic, and pyramidal, all having a 1/3 $\langle 11\bar{2}0 \rangle$ burger's vector. Although, 2nd order pyramidal systems, which have a burger's vector of 1/3 $\langle 11\bar{2}3 \rangle$, can sometimes be activated at elevated temperatures, there are no primary c+a modes of slip in beryllium. As a result, beryllium has very little ductility parallel to the c direction. Because of this ductility anisotropy and the large grain sizes produced during welding, beryllium welds can be brittle and prone to cracking in response to thermal stresses.

STARTING MATERIAL - Beryllium is produced by both powder and ingot processes. The two processes result in material with different impurity levels, grain structures, and textures, and which will respond differently to welding operations.

Impurity Level and Method of Production - The impurity level of beryllium is essentially dictated by its production method. Powder products (hot pressed block and wrought powder sheet) are the most commonly used forms of beryllium. All commercially available grades of beryllium, structural, instrument, and optical, are powder products. Table 2 contains the compositions of several commercially available grades of beryllium (12).

Beryllium powder is most commonly manufactured by comminuting vacuum cast ingots followed by grinding or milling to produce powder (12). A thin oxide layer forms around the particles during comminution, resulting in powder products having a high BeO content, typically greater than 0.50 wt% BeO. Another production technique currently being developed is atomization. Vacuum hot pressing is the primary procedure for consolidating beryllium powder, although hot isostatic pressing is used for some applications.

Ingot beryllium is manufactured by the induction melting of either beryllium scrap or pebble, bottom pouring, and directionally solidifying the ingot (13). The vacuum induction melting significantly reduces the amount of BeO in the ingot, typically to approximately 0.05 wt%.

Electrolytic beryllium is made by the electrolysis of beryllium chloride to form flake which is then vacuum melted into ingot. Table 2 gives the compositions of both ingot and electrolytic material.

Texture vs. Product Forms - Because of the severe ductility anisotropy of beryllium, it is preferred to have a material with as

Table 1. Physical Properties of Beryllium.

Thermal Expansion	$11.5 \times 10^{-5}/^{\circ}C$ (0-50 °C)
Thermal Conductivity	175 W/m°K
Specific Heat	$C_p = 4.54 + 2.12 \times 10 T^{-3} - 16734T^{-1}$
Melting Point	1287 °C
Density	1.8477 g/cm^3

Table 2. Various beryllium grades.

Element	S-65B	S-200E	S-200F	I-70A	I-220B	I-400A	O-50	Ingot[b]	Electrolytic[c]
Be, min %	99.0	98.0	98.5	99.0	98.0	94.0	99.0	99.3	99.7
BeO, max %	1.0	2.0	1.5	0.7	2.2	4.25[a]	0.50	0.05	0.005
Al, max ppm	600	1600	1000	700	1000	1600	700	725	100
C, max ppm	1000	1500	1500	700	1500	2500	700	700	300
Fe, max ppm	800	1800	1300	1000	1500	2500	1000	1400	560
Mg, max ppm	600	800	800	700	800	800	700	---	10
Si, max ppm	600	800	600	700	800	800	700	400	20
Other, each max ppm	400	400	400	400	400	1000	400	200	200

Attritioned Powder S-200E

Impact ground powder S-65B, S-200F, I-70A, I-220B

Ball milled powder I-400A

a. BeO is a minimum in this case

b. Typical values based upon recent chemical analysis at Brush Wellman

c. Typical values based upon Rocky Flats chemical analysis

little texture as possible. This can be achieved in hot isostatically pressed (HIP) powder products. Hot pressed powder is also a relatively isotropic form of beryllium having a less than 2X random basal plane texture. By comparison, the basal texture of wrought powder sheet beryllium is 10-20X random. As a result, ductility in the plane of the sheet for wrought powder sheet is 10%, but through thickness ductility is nil. Ingot sheet beryllium has substantially less texture than does powder sheet, 2-4X random. Figure 1 shows the texture of rolled ingot sheet beryllium. Accordingly, the ductility of wrought ingot sheet in the plane of the sheet is lower, 5-7%, but the ingot sheet does have measurable through thickness ductility.

The different levels of anisotropy in the two types of beryllium sheet can be traced to the BeO content of the material. During rolling, grains having basal planes aligned with the plane of the sheet are deformed less than randomly oriented grains. The sheet is reheated between passes which causes, in the case of the ingot product, the growth of the more heavily deformed, randomly oriented grains. In contrast, the BeO network in powder sheet prevents grain boundary motion and thus illiminates the mechanism for obtaining a random grain structure (14).

Grain Size Effects - Because of the anisotropy of beryllium, grain size becomes an important factor in determining the ductility and weldability of the various product forms. The average grain size of the powder products can be quite small, ranging from 4-5 microns (I-400) to 20 microns (S-65). A representative microstructure of S-65 beryllium is shown in figure 2. This is a result of the BeO in powder products pinning grain boundaries and thus retarding grain growth. Significant grain growth does not generally occur in powder products until 1100°C, so a fine grain size can be retained by vacuum hot pressing at 1060°C. Without the BeO network, grain growth occurs at a much lower temperature, approximately 800°C. As a result, the as-cast grain structure in ingot source beryllium is not significantly affected by hot working. Warm working reduces the grain size somewhat, but grain sizes routinely achieved in powder beryllium have not yet been obtained in ingot products. For example, 1.4 mm (55 mil) thick ingot sheet beryllium has a grain size of approximately 45 microns. Figures 3 and 4 show the grain size for 3.2 mm thick beryllium powder (SR200E) sheet and ingot sheet, respectively.

III. DIFFICULTIES IN WELDING BERYLLIUM

Weld cracking is the principal difficulty encountered in welding beryllium. Three types of cracking commonly occur, hot cracking, cracking originating at defects, and cracking due to the inherently brittle material being unable to accomodate the thermally induced stress.

HOT CRACKING - The incidence of hot cracking in ingot sheet beryllium is well documented (15-18). The hot cracking is attributed to an aluminum-rich grain boundary film which results from the rejection of aluminum during solidification. Figure 5 shows the phase diagram for Al-Be (19). The partitioning coefficient (k) of aluminum in beryl-

Figure 1. Basal Texture of 1.4 mm thick cross-rolled ingot sheet.

Figure 2 Typical microstructure of S-65 beryllium

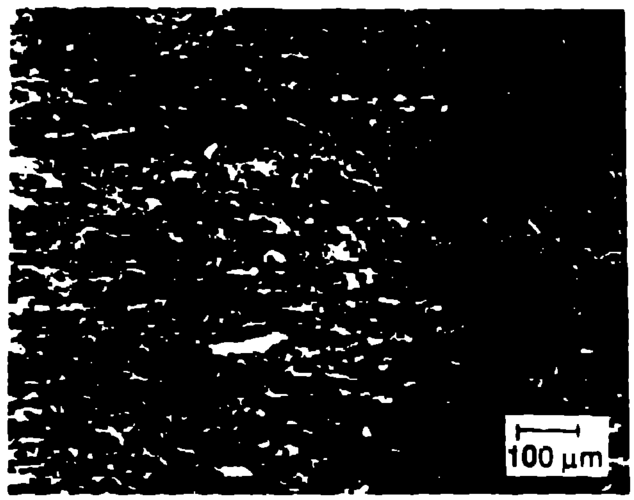

Figure 3. Micrograph of 3.2 mm thick SR200E beryllium.

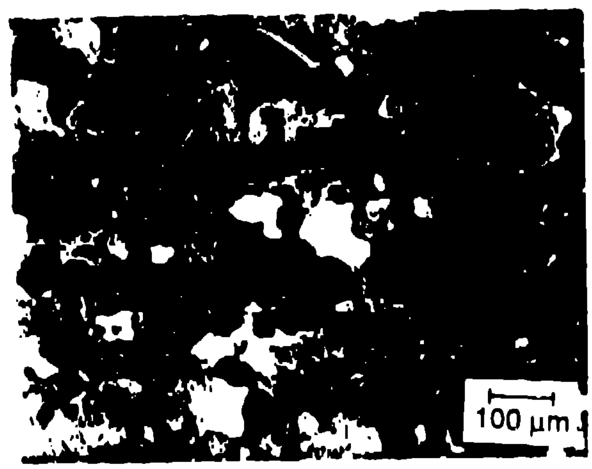

Figure 4 Micrograph of 3.2 mm thick ingot sheet beryllium

um is quite high and the melting point of aluminum (660°C) is much lower than that of beryllium (1289°C). The problem is accentuated at the weld centerline due to the increased concentration of aluminum, grain boundary orientation, and high tensile stresses perpendicular to the weld. A typical micrograph of hot cracking in an ingot sheet beryllium weld is shown in Figure 6. Figure 7, a scanning electron micrograph of the crack surface, shows ductile spikes typical of a fracture surface resulting from hot cracking.

CRACKING ORIGINATING AT DEFECTS - It has been noted (20) that with increases in oxide content of the base metal, there are corresponding increases in the occurrence of both undercutting and weld porosity. These weld defects limit ductility and are caused by a BeO film which forms on the surface of the weld pool (20). This film, which has the appearance of a flux on the molten metal surface, interferes with the welding process and causes increased turbulence in the weld pool. Because of this turbulence, the base metal is unevenly erroded and the oxide film is mixed into the weld pool. The weld pool turbulence also contributes to greater weld surface roughness than that achievable with lower oxide material. Other defects, such as voids and inclusions, may act as crack nucleation sites as well.

SUBSOLIDUS CRACKING DUE TO LOW INHERENT DUCTILITY - The low inherent ductility of beryllium perpendicular to the c direction, combined with the texture present in most product forms, results in very low base metal ductility. During welding, large and oriented grains are formed in the heat affected and fusion zones, further increasing the problem. As a result, beryllium weldments may be subject to sub-solidus cracking when thermal stresses created during welding exceed the material's fracture strength in a direction associated with low ductility. This type of cracking could be at grain boundaries where the long slip paths result in large dislocation pile ups, stress concentrations, and microvoid nucleation.

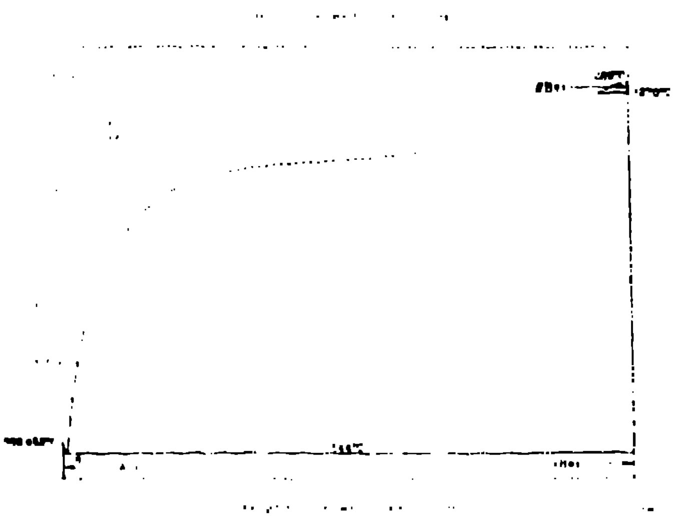

Figure 5. Al-Be phase diagram.

Figure 6. Micrograph displaying centerline crack in ingot sheet beryllium.

Figure 7. Fractograph of centerline crack in ingot sheet beryllium.

Beryllium is also prone to twinning during machining because of the small number of primary slip systems. The twins may act as crack nucleation sites during welding, so it is best to remove 0.10 mm (0.004 inches) from the surface of beryllium parts to be welded.

IV. SOLUTIONS TO WELDING PROBLEMS

With careful control of material and process variables, the cracking susceptibility of beryllium can be overcome and sound welds produced. Discussing first the factors which must be controlled in the starting material:

CONTROL OF THE Fe/Al RATIO - The adverse effect of aluminum on beryllium weldability can be reduced if the aluminum is present as the ordered compound $AlFeBe_4$. Due to the stoichiometry of this compound, it is important to have at least twice as much iron by weight as aluminum in the starting material. On the other hand, if there is insufficient aluminum to form the ternary, the iron may remain in solution or precipitate out as $FeBe_{11}$. The optimum ductility of beryllium occurs at an iron/aluminum ratio of 2.4 (16). Also, high concentrations of $AlFeBe_4$ or iron in solid solution, can lead to increased cracking tendencies (21). Therefore, the total amount of iron and aluminum should be limited. Figure 8 shows the range of Fe and Al contents that have been shown to produce good welds (21). Figure 9 shows the cracking tendency of beryllium as a function of impurity content (21).

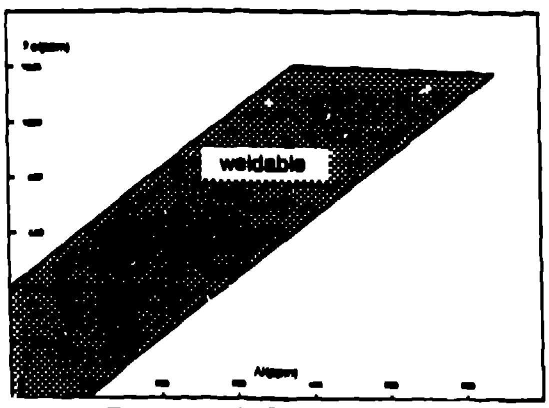

Figure 8. Range of Fe and Al contents in beryllium shown to produce good welds.

REDUCTION OF THE BEO CONTENT - By reducing the BeO content of the base metal, porosity, weld undercutting, and the associated cracking can be reduced. Single pass electron beam welds have been made successfully in 1.6 mm (0.063 in) and 3.2 mm (0.125 in) thick beryllium containing 1.7-1.84 wt% BeO (16,20). Commercially available grades now available have oxide contents as low as 0.5 wt% BeO (O-50), and the BeO content of ingot and electrolytic beryllium are much lower still. However, the maximum permissable BeO content for single-pass, full-penetration welds in beryllium decreases with increasing thickness of the material due to the increased weld pool agitation and more severe stress gradients associated with the higher heat inputs. Therefore, BeO content must be kept as low as possible when welding thick sections.

REDUCTION OF THE BASE METAL GRAIN SIZE - As discussed earlier, the anisotropy of beryllium makes grain size a concern when welding. The grain size of powder sheet beryllium is fine (20 µm), so the main limitations to its weldability are Fe/Al ratio and BeO content. However, the grain sizes of ingot material are typically large (50-100 µm), but the BeO content is quite low. This suggests that the ductility and weldability of the ingot sheet may be improved by a reduction in grain size. There are two methods th. .an be used to reduce the grain size: 1) redundant working and 2) roll bonding. The redundant working involves iterations of extrusion and compression (22). Grain sizes as

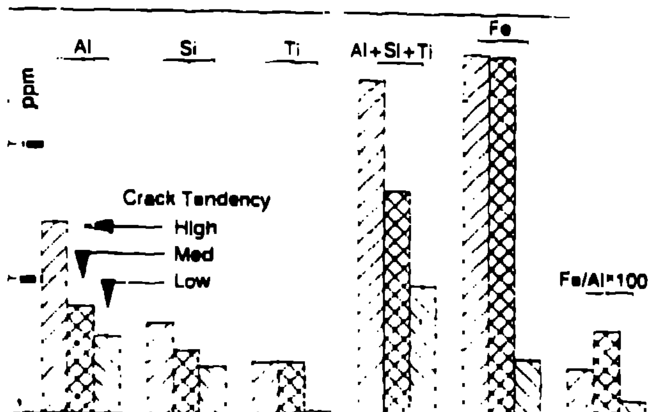

Figure 9. Cracking tendency of beryllium as a function of impurity content.

ine as 2.3 μm have been reported in high purity beryllium using redundant working. By diffusion bonding 10 layers of 0.64 mm (25 mil thick) ingot sheet beryllium, Heiple was able to achieve a grain size of 16 μm in a 6.4 mm (0.25 inch) thick sheet (23).

SELECTION OF WELDING PROCESS AND PROCESS VARIABLES - The selection of weld process and process parameters have a significant effect on the weld composition and structure, and the thermal stresses developed. Thus, proper control of process variables can be used to reduce weld cracking. In general, welding operations should be designed to minimize heat input and grain growth, minimize thermal stresses, and reduce the concentration of weld defects. Beryllium is most commonly welded using gas tungsten arc (GTA) and electron beam (EB) processes. The electron beam technique has the advantage of producing welds with a high depth to width ratio and a narrow heat affected zone. The narrow fusion zone and lower heat input reduce the thermal stress and distortion thus reducing the tendency for cracking. The high depth/width ratio of electron beam welds also makes single pass welding possible in many cases, thereby reducing overall heat affected zone size.

Although the heat inputs are higher, beryllium can also be welded by pressurized gas metal arc (PGMA) and gas metal arc (GMA) processes. Of these PGMA is the preferred option. The benefits of the pressure are two-fold: reduction of porosity and reduction of the arc column diameter.

Grain Structure - Soliditciation during welding occurs primarily by epitaxial growth, resulting in large, highly oriented, columnar grains. In addition to heat input, the grain structure of the fusion zone is influenced by the weld speed. As the travel speed increases, the weld pool tends to become more elongated and grain growth stops abruptly at the centerline of the weld with little change in direction. These welds have been found to have the poorest resistance to hot cracking (24).

Thermal Stresses - Because of the cracking propensity of beryllium, it is important to control the thermal stresses. Thermally induced stresses are related to the local cooling rates and temperature gradients developed during welding. Both the cooling rates and stress gradients can be reduced by the application of preheat. Preheating also increases the ductility so that thermal stresses result in plastic flow rather than cracking. Crack-free full penetration welds have been achieved in ingot sheet beryllium up to 1.5 mm (0.060 inches) thick using a preheat of 400°C (21). Low oxide powder source beryllium (0.5% BeO) has been welded in thickness up to 2.5 mm (0.100 inches) with preheats of 340°C. In general, preheat should be used for autogeneous welding of beryllium in sections thicker than approximately 0.2 mm (18).

The thermal stresses developed during welding are also affected by the design of the weld joint and fixturing. Whenever possible, joint designs should be selected to minimize the restraint of the part. Various joint designs have been used in 1/8" thick beryllium sheet including lap joints, tee joints, corner lap joints, corner butt joints, and butt joints between sheets of unequal thickness (16). However, in lap, corner lap, and tee welds, a sharp notch is present at the interface and will limit the use of these structures to applications with low service stresses. Crack-free full penetration butt welds have also been made in ingot sheet beryllium up to 3.8 mm (0.15 inches) in thickness (21).

Filler Metal Additions - In situations where weld cracking cannot be avoided, aluminum alloys can be added as filler metal. This creates an aluminum-rich fusion zone with a sufficiently low melting point to remain liquid and backfill cracks. The aluminum content of the fusion zone controls the microstructure and the tendency of the weld to crack. A fusion zone content of 30% aluminum is recommended to avoid microcracking (25). The Al-12% Si alloy is most commonly used because it is close to the eutectic composition and thus provides the low melting point and adequate fluidity (25). The drawbacks of adding an aluminum alloy filler metal include a reduction in service temperature and a lowering of the tensile strength of the weld.

V. CONCLUSION

Beryllium, both ingot and powder source, can be successfully welded using gas tungsten arc and electron beam welding techniques. The primary obstacles to welding beryllium are hot cracking, cracking at defects, and ductility limitation or thermally induced cracking. Hot cracking can be reduced by controlling the chemistry of the beryllium to be welded so that an Fe:Al ratio of 2.4 is achieved and the amount of iron and aluminum is minimized. Cracking at defects and ductility limitation cracking can be reduced by lowering the amount of BeO content and grain size of the starting material. Beryllium weldability can also be improved by processes using a slow welding speed, moderate heat input, minimum weld restraint and an appropriate preheat. In some cases, weld cracks can be successfully repaired in situ by the addition of an aluminum alloy filler metal. However, using a filler metal may reduce the service temperature and tensile strength of the welded joint.

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