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Applications in Plasma-Facing Components

Los Alamos
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BERYLLIUM PROCESSING TECHNOLOGY REVIEW FOR APPLICATIONS IN PLASMA-FACING COMPONENTS

by

Richard G. Castro, Loren A. Jacobson, and Paul W. Stanek

ABSTRACT

Materials research and development activities for the International Thermonuclear Experimental Reactor (ITER), i.e., the next generation fusion reactor, are investigating beryllium as the first-wall containment material for the reactor. Important in the selection of beryllium is the ability to process, fabricate and repair beryllium first-wall components using existing technologies. Two issues that will need to be addressed during the engineering design activity will be the bonding of beryllium tiles in high-heat-flux areas of the reactor, and the *in situ* repair of damaged beryllium tiles.

The following review summarizes the current technology associated with welding and joining of beryllium to itself and other materials, and the state-of-the-art in plasma-spray technology as an *in situ* repair technique for damaged beryllium tiles. In addition, a review of the current status of beryllium technology in the former Soviet Union is also included.

1. INTRODUCTION

Beryllium is being considered as the material of choice for plasma-facing components (PFC) for the ITER, i.e., the next-generation fusion reactor. Important in the selection of beryllium have been the materials processing issues that will play a major role in the initial fabrication and repair of PFCs. Key areas that will have a significant impact on the use of beryllium will be the selection and design of beryllium tiles used for high-heat-flux regions, the ability to bond these beryllium tiles to actively cooled substrates, and the maintenance and repair of the beryllium tiles over the lifetime of the reactor. Because the beryllium tiles will be exposed to high-heat-load excursions in critical regions such as divertors, the thermal fatigue behavior of beryllium and the bonded beryllium will need to be characterized in order to prevent cyclic fatigue failures. Current activities within the fusion community are attempting to address these issues through joint collaborative research between the National Laboratories, universities, and industry.

Los Alamos National Laboratory's Metallurgy and Materials Processing Group has been actively involved in the research and development of beryllium and beryllium alloys over the last five years in support of DOE and DOD programs. Both personnel and laboratory space have been dedicated to investigating and promoting the use of beryllium within the defense community and throughout private industry. Beryllium research at Los Alamos has focused on

- advanced powder processing and consolidation techniques for near-net-shape components,

- welding and joining of beryllium to itself and other structural materials, and

- microstructural characterization and mechanical behavior.

One approach which is currently being investigated as a near-net-shape consolidation method of beryllium powder is plasma spray deposition. This process technology is also being considered as

an *in situ* coating-repair technique for beryllium armor in fusion reactors. Past investigations on plasma-sprayed beryllium have shown the need for higher-density deposits, better oxide control, and improved thermal conductivity. Current efforts at Los Alamos are attempting to improve the plasma spraying of beryllium by using current state-of-the-art plasma-spray technology to enhance the quality of the deposit.

At Los Alamos, efforts to weld and join beryllium aim at mitigating this material's lack of weldability (which is usually manifested as cracking) and at achieving diffusion bonding of beryllium to other metals (Al, Cu, Ti, Ta etc.). The effects of impurities, weld grain structure, and thermal and residual stresses are being addressed to identify the crack-nucleating and -propagating events. Studies on diffusion bonding are investigating the effects of time, temperature, pressure, and interlayer material on the integrity of the beryllium bond. Extensive mechanical behavior of beryllium weldments is accomplished through microstructural response and simulation experiments for which Gleeble™ weld-simulation equipment is used.

Beryllium activities at Los Alamos complement many of the critical materials issues that need to be addressed for future use of beryllium in the fusion reactor program, more specifically, issues such as plasma spraying for *in situ* repair and surface regeneration of beryllium armor tiles and joining of beryllium tiles to actively cooled substrates. In order to arrive at a better understanding of the critical issues associated with these processing technologies when applied to beryllium, we did a background review that established baseline information for future investigations.

The following review will focus specifically on plasma-spray technology and the welding and joining of beryllium to materials. Included in this review will be a section devoted to the current state of beryllium technology in the former Soviet Union (FSU). Fine-grained, high-purity beryllium, produced by the Soviet Union, was shown to be less susceptible to cracking during welding than commercially available beryllium in the United States.

The overall intent of this review is to combine both past an present state-of-the-art beryllium technology for future research efforts in which Los Alamos can take an active role.

2. CURRENT STATE-OF-THE-ART IN PLASMA-SPRAYING TECHNOLOGY

Plasma spraying has been in existence for over 50 years as a manufacturing technique for applying coating of metals, ceramics, and composites. Most commercial plasma-spraying operations are done in an ambient air environment; that is why deposits contain entrained oxides in the coatings. Densities of these coatings are approximately 80% to 90% of theoretical density because of the oxidation of the deposited material. Use of inert atmospheric plasma spraying has reduced the oxide content of the as-deposited material; however, the resulting deposit densities (90% 94%) are still unacceptable for many structural applications. Advances in plasma spraying over the last 15 years, specifically the introduction of vacuum plasma spraying, have expanded the scope of plasma spraying from coatings to thick spray deposits (> 15 mm) for potential structural applications. When plasma spraying is done under a reduced pressure condition, higher pressure ratios exist between the plasma spray torch and the operating environment, and they result in gas velocities in the range of Mach 2-3 [1]. Other advantages of vacuum plasma spraying over atmospheric and inert plasma spraying are the following:

a. higher particle velocities, which result in higher deposit densities (>98% of theoretical density),

b. broad spray patterns producing large deposit areas,

c. transferred arc heating of the substrate, which improves deposit density and adhesion, and

d. protective atmosphere for spraying reactive materials.

Plasma spraying, until recently, has been somewhat of a black art, relying on operator intervention to optimize the spray process in order to produce high-quality spray deposits of metals

and ceramics. The current technology base for plasma spraying consists of a wide range of empirical studies that have focused on specific materials applications. Although the scientific base for this technology is lacking, much is known about the plasma spraying of numerous material systems. A growing interest in understanding the fundamental aspects of the plasma spray process, which involves the particle/plasma (melting) and particle/substrate (solidification) interactions, is currently evident within the thermal spray community. Research into understanding the fundamental interactions associated with the plasma spray process is growing, as evidenced by the increased number of publications and presentations given in recent international and national thermal-spray conferences.

Current modeling activities of the direct-current (dc) plasma spray process include the following:

    a.   modeling the effects of chamber pressure on temperature and velocity profiles; [2,3]

    b.   modeling droplet impacts and solidification during vacuum spray deposition; [4] and

    c.   modeling the microstructural evolution of vacuum-plasma-sprayed materials. [5,6]

These activities have complemented past modeling efforts that have focused on dc plasma spraying under ambient pressure conditions.

Substantial efforts are also being directed by the thermal-spray community to develop plasma-spray operating systems that can perform closed-loop control in order to enhance the reliability and consistency of the spraying process over long spraying times. These new developments must rely on state-of-the-art sensor and diagnostic tools for performing real-time monitoring and control of the spraying process. A number of laboratory techniques that show promise in monitoring the plasma-spray process are summarized in Table 1. These techniques may be adapted for real-time control of the plasma spray process. Measurements associated with particle velocities, size, distribution, and particle temperatures, in addition to properties of the plasma jet that control particle melting, will be critical in understanding the dc plasma-spray process. Direct measurements of deposit characteristics (density, defects, thickness, microstructure) would also be needed in order to develop process control algorithms.

PROCESS	MEASUREMENT TECHNIQUE
PLASMA GENERATION efficiency fluctuations	Coolant flow, current, voltage spectral analysis
PLASMA/PARTICLE INTERACTION temperature velocity distribution cold particle numbers	in-flight pyrometry laser velocimetry laser-illuminated video simultaneous velocity and temperature
DEPOSIT surface temperature heat flux splat cooling rate density/defects thickness	pyrometry calorimetry high-speed pyrometry acoustics optics/acoustics

Table 1.
Measurement Techniques Used in Plasma Spraying [7]

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Microstructural evaluation of all the phases of plasma spraying can be accomplished by using current state-of-the-art equipment. Scanning electron microscopy provides important information pertaining to the starting feedstock materials used in the plasma-spray process. Automated, metallographic sample-preparation equipment provides consistent, accurate, distortion-free surfaces for evaluation of the coating characteristics in order to optimize the spray process. Currently available image-analysis techniques and software packages provide accurate and reproducible data pertaining to coating porosity, presence of oxides, foreign particles, and other important coating characteristics.

2.1. Plasma Spraying of Beryllium

Plasma spraying of beryllium was extensively investigated by Union Carbide Speedway Laboratory (UCSL) and the Atomic Weapons Research Establishment (AWRE) in the 1960s and 1970s as a potential near-net-shape fabrication technique to consolidate beryllium. Large, thin-walled shapes, such as cones for re-entry vehicles, presented challenging and costly manufacturing problems because of the direct machining costs of massive forgings or hot-pressed beryllium bodies. I. W. Dunmur's extensive review of plasma-sprayed beryllium is included in *Beryllium Science and Technology, Volume 2* [8]. In this review, a search of the literature before 1960 revealed 18 references to plasma-sprayed beryllium. Much of this work was related to defense and space exploration applications, which involve structural beryllium components and beryllium coatings.

The microstructure and the mechanical and physical properties of plasma-sprayed beryllium in this review referred to beryllium deposits produced by inert atmosphere plasma spraying followed by heat treatments. Results from the (UCSL) showed that, in general, beryllium plasma-sprayed deposits had a reduced grain size (1 to 3 μm) when compared to conventional hot-pressed beryllium. The smaller grain size resulted in increased mechanical properties over the hot-pressed material. Typical properties of plasma-sprayed, sintered, and hot-isostatically pressed (HIP^{cd}) beryllium are given in Table 2. Although much of this information is dated, a significant increase in the mechanical properties occurred as a result of the refined microstructure in plasma-sprayed beryllium, and it should be repeatable.

Condition	Porosity (%)	UTS (MN m^{-2})	Strain to fracture (%)
As sprayed	14	79	~0
Sprayed and sintered	3	241	0.3
Sprayed, sintered, hot isostatically pressed	1.5	413 (average of 10) 464 (maximum of 10)	0.25

Table 2.

Properties of Plasma-Sprayed, Sintered and HIP^{cd} Beryllium [8]

Plasma spraying of beryllium involves a complex layering of individual splatted particles, which creates a 3-dimensional array of interweaving splats, unmelted particles, and entrained oxides. This layered structure results in an anisotropic behavior in both the thermal and mechanical properties of beryllium as was shown in Dunmur's review. Properties in the spray direction (normal to the splat surfaces) were reported to be lower than properties along the planes of the splats. This is typical of plasma-sprayed material in the as-deposited condition. After heat treatment, a more isotropic behavior in properties resulted due to the improved bonding that occurred between the individual splat layers. In order to maximize the physical and thermal properties of beryllium in the as-deposited condition, higher-density deposits will need to be produced. A large fraction of the injected beryllium particles will need to be heated to a molten state before they impinge on the substrate or previously deposited splats. Factors such as gas entrainment can substantially reduce the temperature of the plasma jet, affecting the amount of heat transferred to the injected powder [9]. Both spraying under a controlled atmosphere by using an inert gas and vacuum plasma spraying can result in a larger population of melted particles.

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Previous work quantified the difficulty of melting beryllium by using Engelke's theory [10,11,12], which shows that the difficulty of melting a material is proportional to $LD\rho^{1/2}$ for a particle diameter D, where L is the particle heat content per unit volume of liquid at the melting point over that of solid at room temperature, and ρ is the mean particle density. L is assumed to be roughly proportional to the melting temperature. Using this formulation, beryllium was found to be one of the most difficult metals to melt and comparable in that respect to Al_2O_3. A number of fundamental research investigations involving plasma/particle interactions for vacuum-plasma-sprayed Al_2O_3 have been done and could potentially be used as a first approach when plasma-spraying beryllium under a reduced pressure. The following is a list of comprehensive investigations performed on Al_2O_3 by various investigators; such work may find application when plasma spraying beryllium.

- Temperature and velocity profiles under various operating conditions [13]

- Particle velocities as a function of particle diameter and torch distance [13]

- Effects of particle penetration into a plasma jet [13]

- Radial velocity profiles of injected particles [13]

- The influence of plasma torch design and gas environment on plasma particle momentum and heat transfer [14]

- The effect of chamber pressure on particle velocities in vacuum-plasma-spray deposition [3]

Most of the effort associated with plasma spraying of beryllium has focused on parametric studies to investigate the effects of parameter changes (gas velocity, operating currents, primary and secondary gases, particle size, torch-to-substrate distance, etc.) on the as-deposited density of beryllium. More than 50 different macroscopic variables can ultimately affect the melting behavior and quality of the beryllium deposits. In order to minimize a parametric study of this magnitude, a factorial design experiment can be used to identify the critical parameters for achieving high-density plasma-sprayed coatings of beryllium. Taguchi fractional-factorial testing has been used for both plasma spraying and electric-arc spraying as a means of determining broad-based factor effects on measured operating parameters [15]. This methodology, statistically delineates the impact of each variable on the measured coating characteristics across all combinations of other factors. One factor that can greatly affect the degree of melting of beryllium during plasma spraying will be the time the beryllium particles dwell in the plasma jet stream. Factors which will affect particle dwelling times are the following: plasma gas velocity and temperature, the particle size, shape, and density, and particle injection velocity.

Spraying under reduced pressure conditions will result in very different temperature and velocity profiles for both the plasma jet stream and the injected particles when compared to spraying at atmospheric pressure under an inert atmosphere [2]. Investigations done by M. Smith et al., [3] have found that, when plasma spraying Al_2O_3 (Fig. 1), maximum velocities are reached at an intermediate chamber pressure of 45 KPa (340 Torr). Because of the higher particle velocities at reduced pressures, factors that affect particle dwelling times will need to be optimized using an experimental design approach in order to achieve the highest degree of melting for the injected beryllium particles.

The most recent investigations on plasma spraying of beryllium in the U.S. were done by Battelle Memorial Institute in Columbus, Ohio, in the late 1980s under a controlled, inert environment at atmospheric pressure. Claims of high-density beryllium deposits (>98% of theoretical) using Type IP-70 beryllium powder supplied by Brush Wellman have been circulated. To date, these claims have not been substantiated as demonstrated by the most recent results furnished by the Fusion Technology Division at Sandia National Laboratories.[1] Open-literature publications by Battelle on plasma spraying of beryllium have yet to be published by the principal investigators. Other recent investigations into the plasma spraying of beryllium have been done by French researchers who presented a paper at the 1992 International Powder Metallurgy Conference in San Francisco on "Powder Treatments, H.I.P.

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[1] Private communication with Dr. R. D. Watson of Sandia National Laboratory, Fusion Technology Division, Albuquerque, N.M.
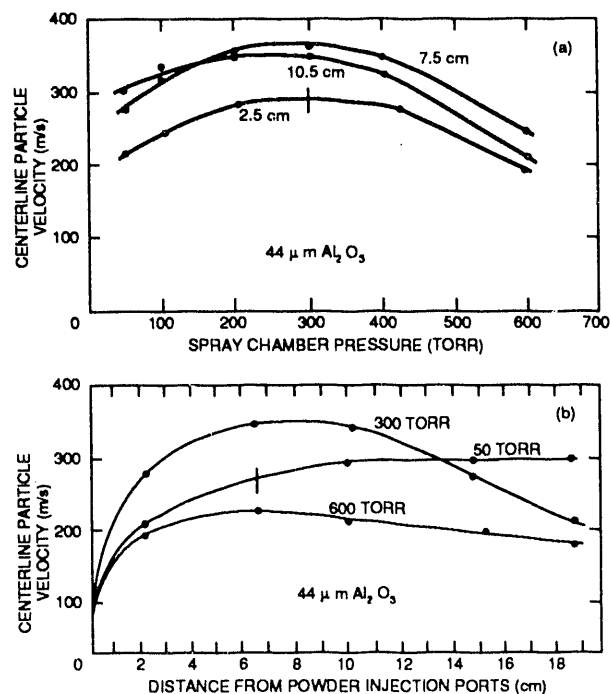
Figure 1.

Measured particle velocitities along the plasma centerline for 44 μm Al₂O₃ spray powder. (a) The effect of chamber pressure on particle velocity at three distances from the powder ports. (b) Velocity profiles at three representative chamber pressures.

	DENSITY	POROSITY (%)
BORON	2,13	9
BORON CARBIDE	2,10	17
BERYLLIUM	1,74	6
BERYLLIUM+ SILICIUM	as sprayed 1,70	8
BERYLLIUM+ SILICIUM	after heat treatment 1100°C 1,81	2

Table 3.
Beryllium Plasma Spray Results from French Researchers

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Consolidation and Plasma Spraying Applied to Beryllium." This investigation used spherical, high-purity beryllium powders as powder feed stock material for plasma spraying. Other activities by French researchers on plasma spraying deposition of beryllium were presented at Los Alamos National Laboratory in 1990.[2] Plasma spraying of beryllium and other materials using cryogenic cooling of the substrate was developed to enhance the as-deposited densities. Results of the investigations are shown in Table 3. These results indicate that the effects of post-heat treatment and the addition of elemental silicon can influence the density and porosity level of plasma-sprayed beryllium. These results are similar to those reported in I. Dunmur's review [8]. A literature search shows that more recent activities in plasma spraying of beryllium have been directed towards the application of *in situ* repair and surface regeneration of divertor regions in fusion reactors [16,17,18]. To date, plasma spraying of beryllium has not been reported since the activities performed at Battelle, Columbus. Los Alamos National Laboratory has presently started vacuum plasma spraying of beryllium (January of 1993).

2.2. Post Heat-Treatment

Investigations into the effect of heat treatments on spray deposits of beryllium have shown a substantial increase in density after elevated temperature exposure. Densification curves were established by both AWRE and UCRA groups to address the reduction in porosity in the as-sprayed deposits after heat-treatment [8]. Temperatures at which densification started depended strongly on the degree of melting and splatting of the beryllium feedstock powders and the subsequent as-deposited densities. Particles that showed extensive melting and splatting upon impact resulted in better intimate contact with the underlying material. During heat treatments, reduced diffusion distances between individual splat layers enhanced the sintering behavior of the plasma-sprayed deposits. Minimization of the oxide layer thickness at the splat boundaries also contributed to enhanced cohesive bonding between individual splat layers. Plasma spraying of beryllium, in which higher-purity powder with a reduced BeO content was used, showed increases in the as-deposited densities after heat treatments [8]. The availability of spherical, low-oxide (.09%) beryllium feedstock powder, produced by centrifugal atomization at Los Alamos, may have a significant influence on the melting behavior and splatting characteristics of spray-deposited beryllium. A comparison between the centrifugally atomized powder and impact-attritted powder will need to be conducted in order to determine possible significant differences in the melting behavior of the two processed beryllium powders.

Use of current state-of-the-art powder synthesis techniques to provide unique feedstock powders of beryllium and beryllium composites may also enhance the melting characteristic of beryllium. Conventional powder blends of beryllium with various additives, such as silicon or beryllium alloys, can be used to enhance or modify the melting behavior of the beryllium feedstock powders. Investigations of atomized nickel powders have shown a significant effect on the melting behavior due to alloying additions [6]. Melting of alloyed powders was shown to occur most often along the interdendritic and intercellular regions of the starting powder. An observed increased rate of melting, for the alloyed powders was due to the increased melting paths of the more segregated alloys. For pure materials, a sharper structural transition from completely solid powders to fully melted powders resulted. Reactive plasma spraying may also be used in modifying the beryllium feedstock powders by causing the surface of beryllium powders to react chemically with a reactive gas precursor. Investigations have shown the potential use of this technique to form either surface layer compounds on injected particles or submicron precipitates within spray deposits [19].

To achieve full density in beryllium-spray deposits, alternate methods of post consolidation aside from elevated-temperature exposures should be considered. Investigators are currently evaluating laser surface treatments on plasma sprayed materials as an alternative method to elevated-temperature exposure.[3] Application of laser surface treatment is currently being investigated by NASA to increase the as-deposited densities of spray-formed NARLOY-Z on critical areas that require high thermal conductivity. Preliminary investigations have shown that this technique may be used in the on-site conditioning of materials intended for components with a large surface area.

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[2] Private communication with M. Houdayer and F. Tourenne, *Commissariat Al'Energie Atomique*, Centre de Bruyeresle Chatel, France.

[3] Private communication with Dr. J. S. Singh of NASA, Marshall Space Flight Center, Huntsville, Alabama.

2.3. Controlled Porosity in Beryllium Produced by Plasma Spraying

Development of materials with controlled porosity is being considered for plasma-facing components as a way of limiting the behavior of thermal fatigue cracking that occurs in beryllium upon thermal cycling. For most mechanical properties (uniaxial and biaxial yield, ultimate strengths, and ductility), the presence of porosity will result in a reduced mechanical behavior. Fracture toughness, however, behaves in a different way with increasing porosity as demonstrated in Figure 2. Toughness was shown to increase to a maximum in beryllium with .05 fractional porosity. This was followed by a decrease in toughness with additional porosity. The reasons for this toughening effect have been attributed to an interruption in the crack front caused by either the pores acting as blunt features for the crack front or the flaws causing multiple crack nucleation, which results in additional fracture surface area and energy absorption [21]. The effect of porosity on thermal fatigue behavior may also show a similar result. Investigations of thermal-barrier coatings (TBCs) produced by plasma spraying have shown enhanced thermal-fatigue behavior due to the presence of porosity [22]. Increases were attributed to an increased work of fracture caused by crack deflection and reduction in crack-tip stress intensity (because the stress is distributed over a larger volume).

Efforts were directed at producing controlled uniform porosity in plasma-sprayed beryllium deposits. The following processing techniques were used in these investigations:

- control of particle-size ranges to achieve desired porosity levels while spraying normal to the substrate;

- variations in gun-to-substrate distance to reduce the average tempc.ature of impacting particles;

- changes in spraying angle to evaluate the effect of the angle of incidence on porosity; and

- inclusion of additives into the powder feedstock; the additives can subsequently be removed from the deposits by leaching.
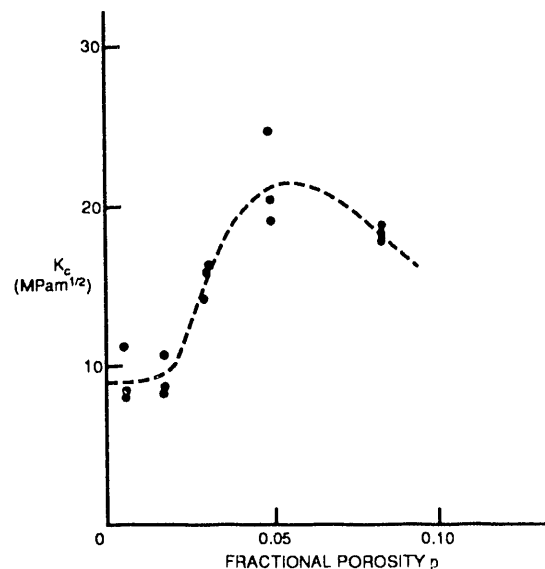
Figure 2.
The effects of porosity on the fracture toughness of plasma-sprayed and sintered beryllium.

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The effect of particle size on porosity for plasma-sprayed beryllium are shown in Table 4. Porosity levels as high as 23.48% could be achieved by using narrow-size fraction powders sprayed under certain processing conditions. The effect of porosity as a function of gun-to-substrate-distance is shown in Figure 3. Porosity levels increased with larger distance from the substrate (a distance of 3 to 4.5 in. produced approximately 20% porosity). The effect of porosity as a function of angle of incidence and spray distance are given in Figure 4: the greater the angle of incidence at a specific gun distance, the higher the porosity levels. The highest porosity levels achieved were at a gun distance of 3.75 in. with an angle of incidence of 54 degrees from normal.

Particle Size Range (microns)	Real Density (g/cc)	Bulk Density (g/cc)	Porosity (%)
12.5 –42	4.31	3.75	12.99
11 -33	4.35	3.87	10.97
10 –25	4.30	3.29	23.48
10 –25	4.30	3.45	19.75
10 –25	4.30	3.68	14.41
10 –25	4.34	3.82	12.09
10 –25	4.29	3.75	12.68
10 –25	4.35	3.80	12.77
10 –25	4.30	3.65	15.17
10 –25	4.26	3.67	13.80
10 –25	4.23	3.65	13.78
10 –25	4.32	3.74	13.39
28 –60	4.17	3.62	13.24
32 –52	4.16	3.57	14.33
4.8 –16.5	Would not deposit		
24.5 –35	4.16	3.66	11.81
24.5 –35	4.18	3.70	11.49

Table 4.
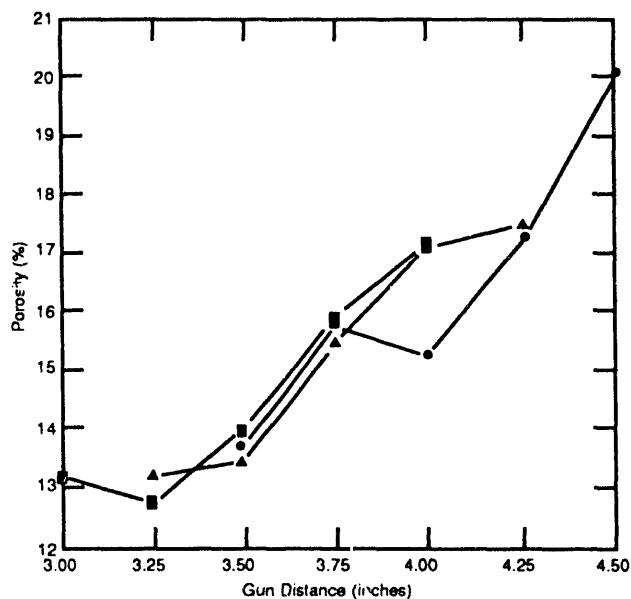Particle Size Range Versus Porosity

Figure 3.
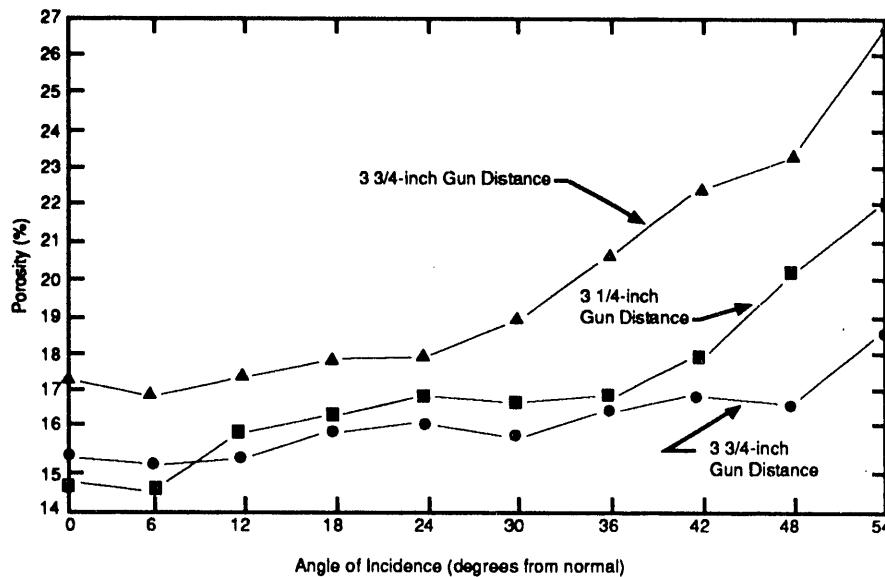Porosity as a function of the gun distance.

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Figure 4.
Porosity as a function of the angle of incidence.

2.4. Atmosphere Control Requirements for Spraying Beryllium

Research to minimize the oxygen and nitrogen levels during the plasma spraying of beryllium was conducted by Union Carbide. A number of factors were researched in order to identify atmosphere control requirements:

- the degree and source of air contamination experienced in a plasma spray chamber, which was designed and built for inert-atmosphere operations,

- the amount of oxygen and nitrogen incorporated into the spray deposits under conditions that ranged from less than 500 ppm of O_2 in the spray chamber to 21% O_2 (air);

- the effectiveness of chamber evacuation and backfilling with inert gas versus a continuous purging (gas displacement) with inert gas.

Experimental results indicated that increases in O_2 and nitrogen occurred in the spray deposits when spraying in a chamber with an O_2 content as low as 15 ppm, Table 5. Factors such as the presence of O_2 and nitrogen adsorbed on the surface of the powder feedstock and the O_2 and nitrogen introduced through the plasma and powder processing gases, were shown to contribute to the increases in O_2 observed in the deposits. Increases in oxygen in the spray chamber (up to 1% O_2) showed little additional changes in O_2 in beryllium deposits after an initial saturation point of oxygen. Analysis of the oversprayed particulate, which is potentially recycble, also showed the same extent of oxygen pickup.

In order to achieve successful recycling of the oversprayed material, the equipment design and operating procedures were reevaluated and the inert atmosphere control was maximized. The preferred concept was to use a spray chamber that was built with the same integrity as a high-vacuum chamber. The chamber was initially gas-purged to a low level of oxygen, and then the spraying process began. This was in contrast to the earlier procedures that required evacuations and chamber backfill to achieve reduced oxygen levels. Procedures for gettering the processing gases during the spray process were not investigated. Current state-of-the-art gettering furnaces for high-temperature and high-vacuum applications are available; they can provide ultrapure inert gases to the plasma spray torch.

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| Specimen Number | Powder (%) | Coating (%) | Increase (%) | Chamber Oxygen (ppm) | |
				Oxygen Analyzer	Sample Bottle
1	0.36	0.65	81		(1)
2	0.36	0.88	144		(1)
3	0.36	0.52	44	75	
4	0.36	0.52	44	50	
5	0.39	0.54	38	90	
6	0.37	0.49	32	40	
7	0.40	0.47	18	30	
8	0.37	0.51	38	21	345 (N_2 - 2, 154 ppm)
9	0.37	0.51	38	18	232 (N_2 - 1, 870 ppm) 125 (N_2 - 1, 136 ppm) 87 (N_2 - 944 ppm)
10	0.37	0.51	38	15	

(1) Chamber evacuated and backfilled with argon. Oxygen content about 0.5 volume percent.

Table 5.
Sprayed Deposit Oxygen Content Versus Chamber Oxygen Content

3. WELDING AND JOINING BERYLLIUM

The following survey of the welding and joining of beryllium is primarily a compilation of two recent surveys conducted at LANL [23] and Lawrence Livermore National Laboratory [24]. The literature was reviewed to establish the current state-of-the-art processes used to join beryllium to itself and to other alloys. The main processes that have been utilized in fabricating various beryllium components include gas-metal-arc and gas-tungsten-arc welding, electron beam welding, resistance welding, brazing, and diffusion bonding. Mention will be made of electroplating bond studies of copper on beryllium for high-strength, high-conductivity beryllium bonds for low-temperature applications.

Although these joining processes have been used successfully for specific beryllium components, the quality of the metal joint is very sensitive to the joining process parameters, the preparation of the faying surfaces, and the metallurgical properties of the beryllium material. The main limitation on welding beryllium is its crack sensitivity, which is affected primarily by the metallurgical characteristics of beryllium itself. The survey discusses these limitations and suggests possible material and processing approaches for improving the metal joint properties of beryllium.

3.1. Beryllium Characteristics

The weldability of a metal is affected by its crystal structure, purity, texture, grain size, and thermophysical properties including the coefficient of thermal expansion (CTE), thermal conductivity, specific heat, melting point, and density (see Table 6). The hexagonal close-packed (HCP) structure of beryllium has the smallest c/a ratio of all HCP elements, 1.568 compared to the ideal c/a ratio of 1.633 for the structure of other HCP elements. The metal has only three primary slip systems and no primary c+a modes; beryllium has therefore very little ductility parallel to the c direction. The large, oriented grains that form in the fusion and heat-affected zones during welding accentuate the anisotropic structure present in most milled forms of beryllium. Thermal stresses generated during welding can exceed the fracture strength of the metal along the low-ductility axis. The thermal conductivity and thermal diffusivity of beryllium are higher than for most other metals. The thermal gradient that beryllium can sustain is low due to the high thermal diffusivity of this metal, and

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Thermal Expansion	$11.5 \times 10^6/°C\ (0-50°C)$
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 6.
Physical Properties of Beryllium

accurate control of the weld cooling rate and pool size is difficult because the thermal conductivity and specific heat are anisotropic.

Beryllium metal stock is produced by both powder and ingot processes. These production processes yield material with different impurity levels, grain structures, and textures, all of which respond differently to welding and joining operations. The compositions of several commercially available grades of beryllium are listed in Table 7. Vacuum hot-pressed block and wrought sheet made from powder are the most commonly used forms of beryllium. Beryllium powder is usually made by comminuting vacuum-cast ingots through milling or grinding processes. During these processes, a thin oxide layer forms around the particles resulting in a high oxide content, typically greater than 0.5 wt% beryllium oxide (BeO). By using atomization processes, such as centrifugal atomization, Los Alamos researchers have produced beryllium powders with a lower oxide content, namely 0.09 wt%.

Grades of beryllium and their impurity content

Grade[a]

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

[a] S-200E (attritioned powder);S-65B, S-200F, I-70A, I-220B (impact-ground powder); I-400A (ball-milled powder). [b] Minimum. [c] Typical.

Table 7.
Various Grades of Beryllium

Ingot-grade beryllium, which is obtained by
• induction melting scrap or pebble,
• casting the resulting molten metal, and then
• directionally solidifying the molten metal

contains about 0.05 wt% oxide. The amount of other impurities can vary depending on their content in the feed stock. The electrolytic grade, which contains only 0.005 wt% oxide, is made by the electrolysis of beryllium chloride to form flake followed by vacuum melting into ingot.

Because the ductility of beryllium is so severely anisotropic, processing methods are directed at producing as little texture as possible. Texture can be minimized by consolidating beryllium powder by hot isostatic pressing (HIP). The basal texture of sheet rolled from hot-pressed powder is approximately 10 to 20 times random, resulting in a ductility of 10% elongation in the plane of the

sheet, whereas through-thickness ductility is nil. The ductility of wrought-ingot sheet is lower, 5% to 7% elongation, but the sheet does have some measurable through-thickness ductility.

Because of the anisotropy of beryllium, grain size is an important factor in determining the ductility and weldability of various beryllium components. The average grain size of powder products ranges from 4 to 5 microns in I400 grade beryllium to 20 microns in S-65. The large amount of beryllium oxide present in these materials pins the grain boundaries, and thus grain growth is retarded during high-temperature processing. Much of the fine-grain size present in the starting powder is retained during hot pressing at 1060°C. Without the oxide network, grain growth occurs at a much lower temperature, about 800°C. Warm rolling of ingot beryllium at temperatures below 800°C reduces the as-cast grain size somewhat. Grain sizes of 45 microns have been produced in 1.4-mm-thick sheet compared to 50 to 100 microns in the starting material.

3.1.1. Brazing. Brazing is the preferred and most reliable process used for joining beryllium to itself and other materials. Some of the commonly used brazing alloy compositions and their corresponding brazing temperatures are listed below:

1)	Zinc	427°C–454°C
2)	Aluminum-silicon	566°C–677°C
3)	Silver-copper	649°C–904°C
4)	Silver	882°C–954°C

Aluminum-silicon filler metals, such as BAlSi-2 (7% Si) and BAlSi-4 (12% Si), are suitable for high-strength wrought beryllium since the brazing temperatures are below the beryllium recrystallization temperature. Other brazing compositions that have been used to vacuum-braze beryllium include the silver-aluminum eutectic (28% Al), the silver-copper eutectic (28% Cu), silver-5% lead, silver-15% lead-20% copper, copper-18% lead, titanium-6% beryllium, and titanium-copper-indium. Sterling silver (less than 8% Cu) is preferred over pure silver for some applications because it exhibits improved wettability. Other commonly used silver compositions include BAg-18 (60% Ag-30% Cu-10% Sn) and BAg-19 (7% Cu-0.2% Li); lithium is added for improved wettability for brazing high-temperature joints. The shear strengths of several brazing alloys are listed in Table 8.

Brazed Alloy Composition	Average Shear Strength, ksi (MPa)	
Silver — Lithium (0.2%)	30.0	(206.8)
Silver — Copper (28%)	35.0	(241.3)
Easy — F10 (50 Ag, 15.5 Cu, 16.5 Zn, 18 Cd)	44.0	(303.4)
Zinc	12.0	(82.7)
Aluminum-Silicon (12%)	15.0	(103.4)

Table 8.
Strength of Beryllium Brazed Joints

Because beryllium reacts with the constituents of most filler metals, brazing should be done under conditions that minimize the formation of intermetallic compounds, namely, rapid heating and cooling cycles, low brazing temperatures with short process cycles, and minimum amounts of filler metal. Only four metals resist formation of stable beryllides below 760°C: aluminum, silicon, silver, and germanium. The joint design, filler-metal selection, and choice of processing cycle are further complicated by the low ductility of beryllium. The low ductility is aggravated by the presence of structural discontinuities, such as surface scratches, notches, and asymmetrical stress patterns produced by single-lapped joints. The parts must be handled carefully, and joint configurations such as butt, scarf, step, and double-lapped joints are preferred for structural designs. Beryllium parts should

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be degreased and pickled in 10% hydrofluoric and nitric-hydrofluoric acid mixtures followed by ultrasonic rinsing with deionized water to remove oxide just prior to brazing. Precoating the faying surfaces by vacuum metallizing or electroplating with silver, titanium, copper, or aluminum prior to brazing enhances the wettability of various filler metals. Beryllium is usually brazed in purified argon, although helium and vacuum of less than 10^{-3} torr are also suitable.

In summary, the fabrication of complex, multicomponent beryllium assemblies by brazing has been used extensively and successfully. By proper brazing alloy and processing parameter selection, the joint can perform at temperatures that approach the base-metal capability with excellent stress distribution and heat transfer characteristics.

3.1.2 Diffusion Bonding. Diffusion bonding or solid-state welding is occasionally required for special applications in which 1) very little foreign metal is permitted in the structure, 2) direct fusion welds are unacceptable because the thickness is too large for crack-free welds, 3) the structure cannot survive the preheating required for crack-free welds, or 4) the required dimensional control cannot be achieved with a fusion weld. For these applications, beryllium can be diffusion-bonded directly to itself or with the aid of a thin interface foil of another material.

The direct diffusion-bonding process requires temperatures of 1120°C and applied pressures of several hundred psi. The load pressure can be applied by differential-thermal-expansion tooling, direct application of a gravity load normal to the surface interface, and canning-HIP-decanning operations. The mating surfaces must be very flat (5-microinch finish) and clean so as to make intimate contact required for interatomic bonding. Initial contact on the faying surfaces is made between surface asperities when the load is applied. Further contact is achieved by plastic yielding and creep deformation.

Activated diffusion bonding can be performed at lower temperatures, typically 875°C, with a higher starting load of 2000 psi. As with direct diffusion bonding, cycle times can run from 4 to 5 hours, with at least 1/2 hour at the highest temperature. Nickel foils, 10 to 12 microns thick, have been used as an interlayer material. High-strength joints have also been formed using a 500-micron-thick electroplated silver interlayer and a 225°C bonding temperature. Aluminum and copper foil interlayers have also been used to aid diffusion bonding with the results influenced by the thickness of the sheets to be bonded and their BeO content.

Joints with strengths close to the base metal strength have been produced repeatedly with resulting distortions of less than 2.5 microns. The diffusion bonding process can be used to join beryllium to most other metals; this process is generally impossible with fusion techniques except for Be-Al joints. However, the process is technically complicated and is only applicable to flat surface joints.

Within the National Defense Programs diffusion bonding of beryllium to other materials will add to the current understanding. Data generated from these studies will provide technical information needed in addressing current problems associated with the diffusion bonding of beryllium tiles to actively cooled substrates in the fusion technology program.

3.1.3. Welding. An ideal welding process for beryllium would
- produce a strong, ductile joint without cracks or other defects;
- produce minimal property degradation in the joint and adjacent base metal;
- be adaptable to a variety of joint configurations; and
- be inexpensive and reliable.

No joining process devised to date has met or even approached all of these goals simultaneously for beryllium. However, several, different welding techniques approach the various goals with different degrees of success.

Processes for welding beryllium include gas metal-arc (GMA), pressurized inert gas metal-arc (PIGMA), electron beam (EB), and resistance spot welding. The GMA process requires a filler wire of aluminum alloy (ALCOA 718, Al-12% Si) and extreme cleanliness of the surfaces to be welded. Weld strengths of 18-24 ksi have been produced with a double weld pass of a 0.030-in.-diameter wire fed at 900 in./min, and a surface speed of 90 in./min Other process variations include reverse polarity arc current, various argon and/or helium gas flow rates, and different numbers of weld passes. The PIGMA process differs from GMA in that it is performed in an inert-gas chamber operated above atmospheric pressure. The elevated pressure reduces the diameter of the arc column and it reduces the porosity of the weld.

EB welds have been made in beryllium without aluminum filler, but cracking is very difficult to avoid, and the process is limited to sheet material that is 20 to 30 mils thick. Typically, a thin layer of aluminum is placed in the weld by either vapor-plating or spot-welding a thin shim (7 mils) of aluminum on one surface of the weld joint. Typical weld parameters for a joint requiring a 0.1-in. penetration are 70 kV, 7.5 mA, and a surface speed of 14 in./min, with the beam focused at 1/4 in. above the joint. Again, surface cleanliness is very important. Compared to the arc welding processes, EB produces a much narrower fusion zone, and it releases substantially less heat into the joint. Thus, thermal strain and distortion are reduced. The smaller fusion zone requires that less filler metal be added to the joint. More filler metal reduces the surface temperature and tensile strength of the joint. Oxidation during EB welding is minimal because of the vacuum environment.

Weld cracking is the principal difficulty encountered in welding beryllium. In addition to the low inherent ductility of beryllium in the crystallographic c-axis direction, beryllium suffers from hot cracking and crack initiation at defects. Hot cracking is attributed to an aluminum-rich grain boundary film that is produced by the rejection of aluminum during solidification. The partition coefficient of aluminum in beryllium is 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 because of the increased concentration of aluminum, grain boundary orientation, and the high tensile stresses perpendicular to the weld.

The adverse effect of aluminum can be reduced if the aluminum is present as the ordered compound $AlFeBe_4$. This stoichiometry dictates that at least twice as much iron by weight as aluminum be present in the starting material. The optimum ductility of beryllium occurs at an Fe/Al ratio of 2.4, whereas high concentrations of $AlFeBe_4$ or iron in solid solution can lead to increased cracking. The iron and aluminum contents that have been shown to produce good welds are given in Figure 5. The cracking tendency of beryllium as a function of impurity content is given in Figure 6. Increased cracking occurs with increased oxide content in the base metal, with corresponding increases in undercutting and weld porosity. The BeO film that forms on the surface of the weld pool interferes with the welding process by increasing turbulence in the pool; the turbulence unevenly erodes the base metal and mixes oxide into the pool. The included oxides, voids, and surface roughness act as crack nucleation sites. Thus, higher-purity beryllium can be welded with improved results as reported in the review of Russian beryllium technology.
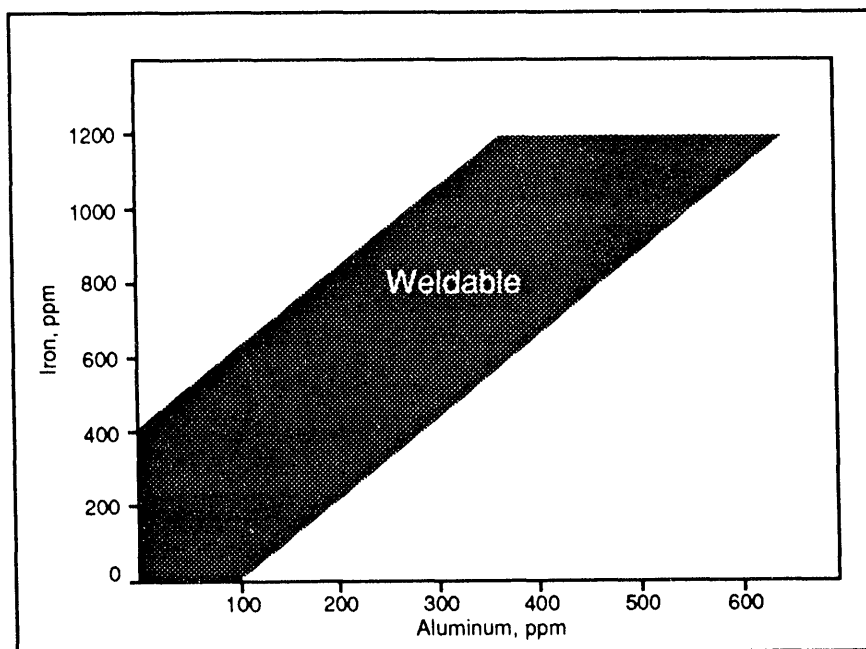

Figure 5.
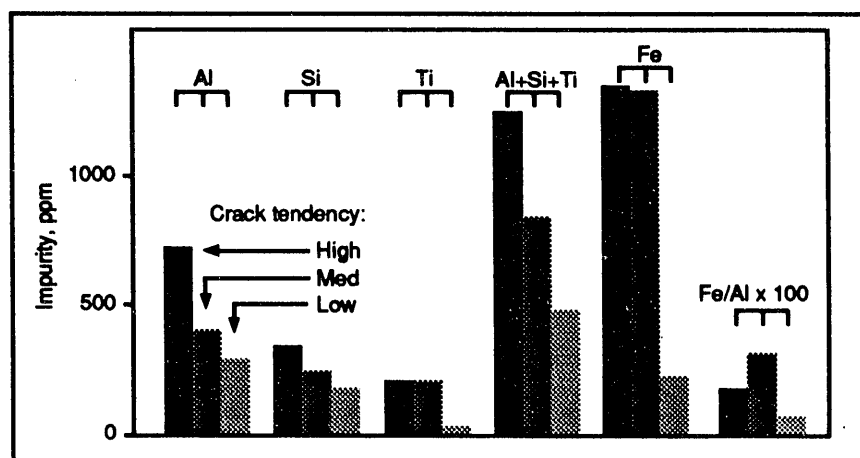Range of iron and aluminum contents conducive to sound welds.

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Figure 6.
Cracking tendency of beryllium as a function of impurity content.

Although there have been many investigations of the various factors that affect the weldability of beryllium, the technology for welding beryllium would benefit from a more in-depth study of how these factors influence the weld microstructure and how they control the properties of the weld. The Welding and Joining Section within the Metallurgy and Materials Processing Group (MST-6) at Los Alamos has initiated such a program to characterize and/or model the impurities, the grain structure of the weld, and thermal and residual stresses in various grades of beryllium. The beryllium materials selected for study contain a range of impurities. The welding processes for this investigation will focus primarily on EB and laser processes, although diffusion bonding and other welding processes will also be addressed.

Welding conditions will be simulated and tested with a dynamic, thermal-mechanical, metallurgical system, the Gleeble™. This system is capable of simulating welding processes under precise control using a unique, resistance heating system that can heat specimens at rates of more than 20,000 degrees C/sec and can hold steady-state equilibrium temperatures within ± 1 degree C. Integrated, mechanical testing is capable of exerting as much as 9 tons of force in tension or compression at extreme rates, ranging from 1000 mm/sec to .00002 mm/sec. Combined thermal-mechanical testing can be performed using this equipment by utilizing high-speed thermal and high-speed servo-loops under simultaneous control over a wide range of testing conditions. An area of interest to the fusion technology community will be to evaluate the thermal-fatigue behavior of beryllium tiles, joined to water-cooled substrates, under various temperatures and load conditions.

3.1.4. Electroplating. The fusion technology community is evaluating copper electroplated on beryllium to be used for high-strength, high-thermal-conductivity bonds suitable for high-heat-flux regions in the next-generation fusion reactor.

An investigation of copper electroplated on beryllium was done at LANL as part of a program to identify alternate, lightweight materials for space-deployable neutral particle beam systems. Beryllium was selected as a potential, lightweight material due to its high elastic modulus, low CTE, low electrical resistivity, and high thermal conductivity. Since copper coatings are used extensively on components of these systems, coating integrity and dimensional stability on replacement materials were evaluated.

Electroplating of copper on beryllium was done by first degreasing beryllium with trichloroethylene. Beryllium was then chemically polished with a phosphoric-chromic acid solution. A beryllium zincate solution containing zinc oxide, potassium fluoride, and sulfuric acid was used to immerse beryllium samples before plating copper. Samples underwent a cyanide-copper strike prior to plating with udylite bright acid copper at a rate of 25 microns/40 minutes.

Bond strength measurements of electrodeposited copper on beryllium were done under two conditions: in an as-deposited condition, and after cycling five times between 4K and ambient temperature. Tests were done using a punch and die test developed by Dini et al., which results in a uniform shear loading between the two materials [25]. Failure of the electrodeposited copper on

beryllium was defined as a significant load drop resulting from the interfacial fracturing between the two materials, or the separation of the copper from the beryllium. In some cases cohesive failure occurred in the copper deposits instead of adhesive failure along the interface. The total load required to achieve failure was then used to calculate the shear strength of the given bond area. Bond strength results for a number of different materials evaluated under the lightweight materials program are given in Figure 7. The results represent an average of five tests for each sample. A drop in bond strength of the thermally cycled materials was anticipated because of the introduction of thermal stresses during the low temperature cycling. However, after thermal cycling, the bond strength between copper and beryllium increased. In this case, failure occurred cohesively in the copper instead of along the interface. Bond strength increases were attributed to work hardening along the copper interface after thermal cycling.
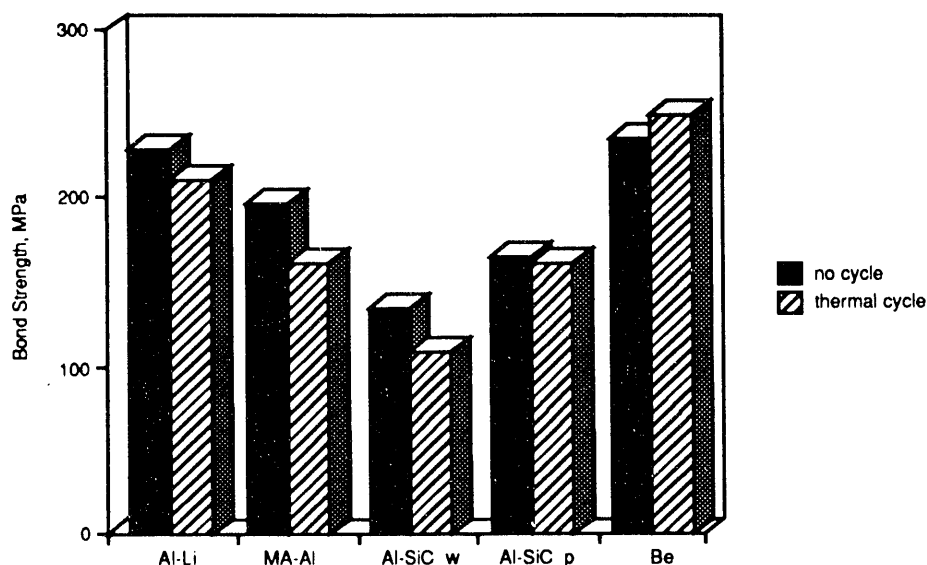

Figure 7.
Bond strength results for uncycled and thermally cycled copper-electroplated materials.

4. BERYLLIUM IN THE FORMER SOVIET UNION (FSU)

It would be incorrect to think of beryllium in association with "Russia" because not only is one of the principal ore deposits in Kazakhstan, but the refining plant is also located there, in the town of Ust-Kamenogorsk. Ust-Kamenogorsk is the largest, nonferrous-metal refining locale in the FSU, having large facilities devoted to lead, tungsten, titanium, molybdenum, and other metals, besides beryllium. Much of what is known in the West has been obtained in connection with consulting activities following the September 1990 explosion in the beryllium plant located in Ust-Kamenogorsk.

Beryllium has been produced in the FSU since 1932, according to a recently translated book entitled *Beryllium*, by B. I. Kogan, K. A. Kapustinskaya and G. A. Topunova. The book was originally published by "Nauka" in Moscow in 1975; the information is somewhat dated. Nevertheless, the book contains a very complete compilation of information, ranging from the characteristics of known beryllium ore bodies around the world to a catalog of beryllium applications (drawn mostly from western sources), including mention of the use of beryllium for the top ten meters of the mast for the 1970 winner of the America's Cup, the yacht "Intrepid."

Open-literature technical publications on beryllium have been quite numerous over the years, suggesting that the technology is well developed, and that there are many applications that were not discussed in the Russian book published in 1975. Various publications, including the one cited above, have contained information on the purity of various Soviet beryllium products. These compositions are listed in Table 9, along with the composition of a high-purity beryllium sample believed to be of Soviet origin and a current U.S. beryllium specification. The Soviet powder grades appear to be

PRODUCT	Cast Ingot, Technical		Powder		High Purity Block	Current U.S. Specs
ELEMENT	Grade 1	Grade 2	Grade 1	Grade 2		
Si	200 ppm	400	150	300	680	600
Al	400	700	300	400	10	600
Mg	200	400	100	150	2	800
Mn			200	300	27	400
Fe	1500	3000	2500	3500	330	1000
Ni	300	500	300	450	10	<400
Cu	200	300	200	400	54	<400
C	1000	1500	1200	1500	50	1000
O_2	2000	2000	3000-12000	4000-12000	9600	12000

Table 9.
Composition of Russian Beryllium Products

comparable to the U.S. specification. The ingot material is much lower in oxygen and iron, since both of these impurities are associated with the grinding-to-powder process.

The high-purity sample could have been purified by vacuum distillation, as it is believed that this process has been employed by the Russians on an industrial scale for many years. The sample was fine grained, suggesting that it would have good mechanical properties, but it was too small to allow scientists to obtain test specimens. Crystallographic texture indicated that the material had been extruded, either as a part of or following its consolidation from powder. Its powder origin is suggested by the amount of present oxide and silicon, which would have been added as a densification aid. The higher iron content could have been caused by the grinding process. Several bead-on-plate EB weld passes were made on the small block of material, none of which showed evidence of cracking. The same procedure led to cracks in U.S. specification material. Subsequent attempts to obtain more of this type of material from the former Soviet Union have been unsuccessful.

Several significant papers were presented by Soviet scientists at the international conference on beryllium, held in London in 1977 [26]. In one of these presentations, Soviet scientists claimed to have achieved fine-grain-size (10 micron) beryllium with minimum preferred crystallographic orientation and room temperature ductility of 20% in three orthogonal directions. The material was made by a thermomechanical processing treatment involving redundant working at temperatures of 1000°C and lower, as the grain size became finer. It was also shown that this beryllium material was superplastic at elevated temperatures [27]. Despite the potential usefulness of untextured beryllium with this level of room temperature ductility and superplastic properties, no serious attempt has been made in the U.S. to duplicate this result. (It should be noted that such ductility levels can be achieved in sheet that is rolled from powder-billet starting material, but the sheet is highly textured.)

Russian papers on beryllium were retrieved in a previous study in which a Dialog search of the Metadex database from 1978 to 1988 was conducted. The search identified a total of 28 publications. The main emphasis of these publications was on the basic properties of the metal and on the effects of processing, alloying, and impurities on beryllium properties. Twenty-six papers were in this category, while the other two were on refining and welding.

One of the reasons for selecting 1978 as the beginning year for the search was the publication of a major book on beryllium in the United States, *Beryllium Science and Technology,* which was copyrighted in 1978 [8]. By that time, it had become very clear that higher purity would not lead to dramatic improvement in the ductility of beryllium, and that solid-solution alloying approaches could not be employed. In the intervening years, the number of producers of beryllium metal in the U.S. has dropped from two to one, and at the present time there are no longer any operating free world producers outside the U.S. Contributing to this decline in producers has been a shrinking market and increasing concerns about the toxicity of beryllium, which adds to its cost of production and fabrication. Apart from being used in applications that depend on its nuclear properties, beryllium is used for inertial guidance components, because of its high stiffness, and for space shuttle components, including the window frame [28]. Beryllium is facing strong competition from aluminum metal-matrix composites for guidance component applications, as well as for structural components of future spacecraft.

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While the market and decreasing applications of beryllium in the West appear to have brought about a stagnation in alloy and process development, no similar trends appear to be deterring the Russians. Unfortunately, very little is known about the production and application of beryllium in the FSU, and therefore it is not possible to make direct links between certain types of basic properties and the application that would benefit most from property improvements. For example, the ability to form beryllium superplastically into net-shape components would be a potential benefit to almost every application, since it would reduce or eliminate the necessity for machining. Machining adds significantly to the cost of a beryllium part because it can lead to airborne particulate, which is the primary beryllium health hazard. Elaborate precautions must be taken to protect machine tool operators from exposure. Machining also produces surface damage that compromises the mechanical properties, and this surface damage must be chemically removed. Two of the 28 Russian papers dealt with the superplastic behavior of beryllium, [29,30] perhaps not an overwhelming amount of evidence as to the actual use of this process, but of extremely significant evidence when cosidering the total absence of such studies elsewhere in the world.

Four of the Russian papers dealt with topics related to high-temperature structural applications of beryllium—one on oxidation from 700°C to 1000°C [31], one on detailed analysis of impurity effects [32], and two on alloy development [33,34]. A similar number of papers came from western countries, which, clearly, is a much lower percentage of the total. Two of these papers dealt with the application of existing grades to the thermal cycling environment for a fusion reactor [35,36], one dealt with fracture at elevated temperature (up to 300°C) [37], and one dealt with alloying effects of copper on mechanical properties of berylluim at temperatures up to 500°C [38]. The oxidation paper investigates the temperature range over which unprotected Be shows breakaway, or unacceptably high oxidation rates, then goes on to document the improvements resulting from both a surface passivation treatment and an enamel coating. Typical of Russian open-literature publications, neither the treatment nor the coating is described in sufficient detail to allow other interested investigators to duplicate the experiment. Two of the papers which were believed to be sponsored by the All-Union Institute of Aviation Materials because it was co-author by Fridlyander. One of these papers discusses the adverse effect of aluminum (and silicon) impurity in beryllium on the high-temperature strength and on the basis of fundamental phase relationships and formulates a rule for the ratio of certain other impurities to aluminum that will avoid high-temperature problems [32]. The other paper describes an investigation of Be-Cr alloys, and Be-Cr alloys with Ni and V additions, again with emphasis on improving high temperature properties [33]. Such work must be motivated by a clear and pressing requirement. The possible application of berylluim to high-temperature structures would make a major contribution to reducing the structural weight of high-speed aerodynamic vehicles. The possible institutional association further suggests this application.

Finally, a number of conclusions can be drawn from an examination of open literature published since 1978 on beryllium:

- Free-world efforts appear to have dropped significantly during this period, perhaps due to declining demand, high material prices and increased concerns over beryllium toxicity.

- No new processes have been introduced in the West, and reported Russian process and property improvements have not, apparently, been verified.

- Russian application of superplastic forming could be yielding reduced cost and improved properties for a variety of aerospace components.

- Reported Russian work related to high-temperature application of beryllium implies an association with high-speed aerodynamic vehicles.

- The study of high-purity beryllium, likely of Soviet origin, has suggested that capability exists for producing an excellent-quality structural beryllium material that could be welded.

The Appendix contains information on investigators and institutions involved in beryllium research in the former Soviet Union.

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Appendix

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