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Manufacture of beryllium for fusion energy applications

David E. Dombrowski

Brush Wellman Incorporated, Cleveland, OH, USA Received 12 September 1996, accepted 15 November 1996

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Abstract

Beryllium has been used for plasma facing components in several tokamak fusion reactors and is being considered for use in ITER plasma facing components. In addition, it is being considered for use as a neutron multiplier in the ITER breeding blanket and as inertial confinement fusion hohlraums. Production and processing of beryllium metal is described with an emphasis on issues relevant to these fusion energy applications. © 1997 Elsevier Science S.A.

Keywords: ITER breeding blanket; Neutron multiplier; Fusion energy applications; Plasma facing component; Beryllium metal

1. Introduction

Beryllium is a specialty metal which has been used for limiters and divertor tiles in several tokamaks [1-3], and is being considered for ITER plasma facing components and the breeding blanket neutron multiplier [4,5]. Beryllium is also being considered for use in inertial confinement fusion hohlraums [6]. The critical beryllium properties which support these applications vary as much as the application so it is useful for the fusion designer to become acquainted with the advantages and disadvantages of different beryllium forms and with standard processing issues.

1.1. Beryllium uses and properties

Beryllium has a unique collection of properties. As a structural metal it has low density (1.85 g cm^{-3}), and high elastic modulus (303 GPa). The outstanding stiffness to weight ratio (elastic modulus to density) has been invaluable for weightcritical aerospace applications. Beryllium is used both as a neutron reflector in nuclear fission test reactors and as a neutron multiplier. Due to its low mass absorption coefficient for X-rays, beryllium foil windows are widely used in X-ray analytical and medical instruments.

1.2. Critical properties for beryllium uses in fusion

The ability to getter oxygen and other gases from a vacuum vessel interior is the primary property which lead JET to consider beryllium for use in divertor and limiter applications [1]. Beryllium has the strongest chemical driving force to react with oxygen for all metals except thorium and calcium [7]. Thorium is mildly radioactive and has a high atomic number. Calcium is not a

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structural metal and corrodes excessively in air and water vapor. Other attributes considered were low atomic number, and low concentrations of high atomic number impurities. Once these requirements were satisfied, the mechanical properties of beryllium were examined.

The neutron multiplication properties of beryllium (n,2n) reaction for high energy neutrons are well known [8]. No differentiation has been made for this property in terms of compositions, microstructure or mechanical properties, so many different types of beryllium can be used. However, the Japanese breeder blanket design would require that the beryllium grade used can be produced in the form of 1-2 mm diameter pebbles [9].

1.3. Choosing S-65C grade beryllium for JET and ITER

S-65C grade beryllium was chosen for use in JET because it has the lowest BeO and metallic impurity concentration among the Brush Wellman structural beryllium grades. Subsequent mechanical testing showed that it also has the highest elevated temperature ductility of the structural grades. Low cycle thermal fatigue tests conducted by Watson et al. for ITER [10] showed that S-65C has the best low cycle thermal fatigue performance of all beryllium grades.

2. Beryllium supply

2.1. Worldwide supply

Table 1 shows an estimate of the known world reserves of beryllium with the exception of the former USSR and the People's Republic of China. There are an estimated 485 500 metric tons of beryllium in known reserves [11]. Projected need for construction of ITER for beryllium is approximately 17 metric tons for first wall, divertor and ICFRH and RH antennas, and 187 metric tons for the breeder blanket. Known world reserves can easily satisfy these projected needs.

Known beryllium reserves are large, but the full extent of other reserves are largely unknown. This is because beryllium has traditionally been used for low volume, highly specialized applications, principally aerospace, and known reserves have been sufficient to satisfy those modest needs. In addition there are the unknown size of reserves in the former USSR and in the People's Republic of China, and reserves around the world which have not yet been evaluated due to lack of economic demand.

Table l

[illegible]
Federation and China) [11]

Location	Tons of Be
North and South America	344 000
Europe	4000
Africa	103 000
India and Afghanistan	26 500
Australia	7900
Total	485 400

Note: Thus estimate is not exhaustive for those regions shown. There has not been economic incentive to produce an exhaustive survey.

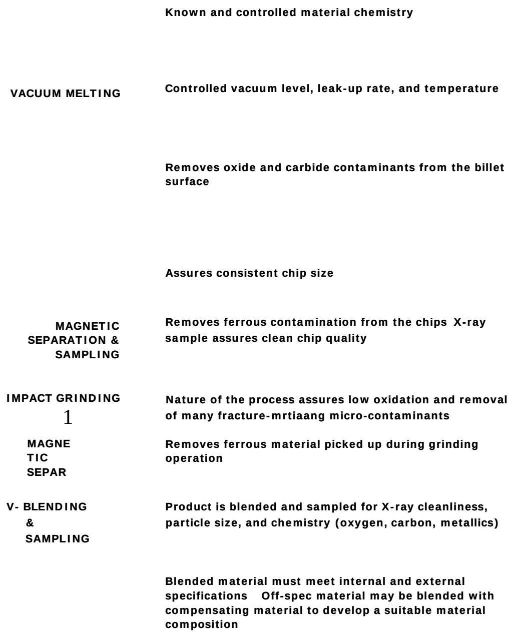

Fig. 1. Impact ground powder processing outline.

Known and controlled input chemistries

Controlled vacuum
Controlled leak-up
rate

Controlled temperature

Controlled 0, content m N, atomization gas
Controlled pressure

200 mesh - remove large particles

MAGNETIC SEPARAT — Removes ferrous processing contaminants

ROLL BLEND - SAMPLE — Sample tested for X-ray cleanliness, chemistry (includes oxygen, carbon, and metallics IFe, Al, Mg, Si, N,. and particle size

Blended material must meet internal and external specifications Off-spec material may be blended with compensating material to develop a suitable material composition

Fig 2. Process flowsheet for production of gas atomized spherical Be powder.

2.2. Brush Wellman supply and production capacity

Commercial production capacity data will focus on the production capacity of Brush Wellman in the USA, which is the only commercial producer of beryllium.

The US Bureau of Mines [12] states that current Brush Wellman capacity is 181 metric tons per year. This is over ten times the projected need for construction of ITER plasma facing components, first wall, ICFRH and RF antennas. Production of beryllium for the breeder blanket would take slightly over a year, depending on the form finally chosen for the blanket. Brush Wellman beryllium reserves are expected to last 46 years at the above production rate, which represents known company reserves of 8346 metric tons. There are significant uncharted company reserves; economic demand has not been great enough to justify their full exploration.

Blended Powder, Ready to V HP	From previous chart(s)
SELECT DIE	Based on thickness and diameter of final part
LOAD POWDER INTO DIE	
LOAD DIE INTO VHP FURNACE	
DE-GAS VHP FURNACE	Removes water vapor, etc from powder particles Controlled heat-up rate, temperature, vacuum levels
	Controlled and fully documented temperature and pressure cycle
REMOVE BILLET FROM DIE	
CHECK PART DENSITY	Water immersion testing
READY FOR ROUGH	

Fig. 3. Process outline for VHP

Blended Powder, Ready to	From or,,,,,, chartlsl
DESIGN HIP CAN	Size based on blended powder tap density measurement
FAB HIP CAN	Clean, rust-free, drawing quality steel Certified welders
LOAD HIP CAN	
DE-GAS HIP CAN	Removes water vapor, etc from powder particles Controlled heat-up rate, temperature, vacuum levels
SEAL HIP CAN	
	Controlled and fully documented temperature and pressure cycle
REMOVE HIP CAN 1),	Typically etched off with HNO_3 Controlled temperature
ECK	Wat", mmersion testing of HIP'd part density
HEAT TREAT FOR TIP RESPONSE CHECK PART DENSITY	800°C heat treatment induces any compressed residual gas in the part to expand, causing thermally induced porosity (TIP) Controlled temperature and vacuum levels
	Density quantifies the thermally induced porosity present, if any
READY FOR ROUGH MACHINING	

Fie. 4 Process outline for HIP.

3. Summary of beryllium production

($Be_4Si_2O_7(OH)_2$) and beryl ($3BeO \cdot Al_2O_3$

ores [13-16]. The strong affinity of beryllium for oxygen dictates a combination of chemical and mechanical extraction methodsfor beryllium metal from the ore. Beryl ore must go through a series of high temperature thermal decomposition steps to prepare it for processing. Heat treatment at temperatures as high as 1700°C followed by a water quench is used to break down the complex beryl structure, followed by another thermal decomposition step at 1000°C. Ball milling is then used to prepare the processed beryl ore for leaching. Sulfuric acid leaching at 325°C is used to dissolve beryllium from the processed beryl ore. By contrast, only sulfuric acid leaching at 95°C is needed to extract beryllium from bertrandite ore. Once beryllium is in solution it is concentrated by solvent extraction and then precipitated as beryllium carbonate. A second hydrolysis step at 160°C is used to precipitate the beryllium as beryllium hydroxide.

Beryllium hydroxide, lime and ammonium bifluoride solution are combined to produce ammonium beryllium fluoride (ABF) salt in aqueous solution. The ABF salt solution is then chemically treated to remove impurities such as iron, lead, manganese and zinc. Vacuum evaporation and a centrifugal separation step produce ABF salt. The salt is decomposed to ammonium fluoride gas and molten beryllium fluoride at 700-900°C in a continuous induction furnace. Solid beryllium fluoride is reduced with magnesium metal to molten beryllium and magnesium fluoride. Upon cooling, a solidified cake of beryllium spherical pebbles, magnesium fluoride and unreacted beryllium fluoride is formed. The solid cake is crushed in a hammer mill and leached with water to remove the beryllium fluoride and most of the magnesium fluoride. A density separation step is used to separate the beryllium from the residual magnesium fluoride. The beryllium is in the form of spherical pebbles at this point. Note that this intermediate beryllium product has been used for breeder blanket research in the pebble bed area.

Beryllium pebbles are processed by vacuum melting to eliminate impurities [15,16]. Molten beryllium is poured into a graphite mold under vacuum and solidified. The graphite mold reacts with the molten beryllium to form a beryllium carbide skin on the outer surface of the ingot. This carbon rich skin is removed using a lathe.

The beryllium ingot must be processed by either the powder metallurgy (PM) process or by extensive rolling to reduce the grain size and obtain the desired mechanical properties. The PM route shown in Fig. 1 is by far more common and has the advantage of producing a fine grain size without generating significant preferred crystallographic orientation (texture) in the final product. Texturing results in highly anisotropic properties. In the PM process [15] the ingot is reduced to large, flat chips by an engine lathe with a 17 tool cutter. These chips are too large to manufacture a useful product, so they are sent through one of several powder-making operations: attrition milling, impact grinding, or ball mill grinding. The goal of powder-making is powder particles with a more isotropic shape and with linear dimensions less than 75 [m. Although rolling the ingot can produce sheet with exceptionally low BeO content, edge cracking during rolling results in high material losses and high costs.

The type of powder-making process used has a significant effect on beryllium properties [13,15,16]. In attrition milling, beryllium chips are ground into powder between a fixed, grooved beryllium plate and a rotating grooved beryllium plate. Attrition milling produces plate-like particles that tend to align preferentially during die loading, resulting in anisotropic mechanical prop

Fig. 5. Structure of hexagonal close packed (hcp) unit cell. The (001) plane is the basal plane ([27])

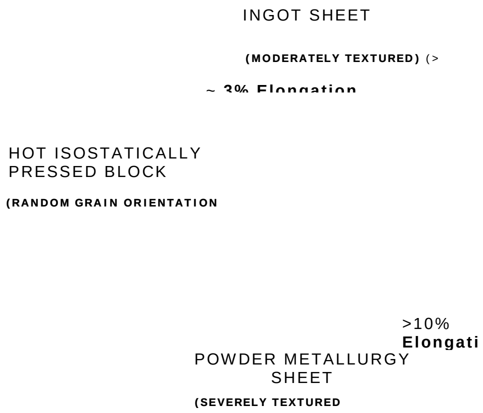

Fig. 6. Relationship between minimum tensile ductility and degree of texturing for a common beryllium grade. The dumbbell shaped symbols represent the hcp unit cell The degree to which these symbols line up represents the degree of texturing [29]

erties. Impact grinding consists of suspending beryllium chips in a stream of high velocity gas and colliding those chips with a solid beryllium target. The blocky particles produced by impact grinding result in a less textured microstructure and more uniform properties in all directions. Ball mill grinding produces extremely fine particles which in turn produce an extremely fine grained microstructure. The largest volume of beryllium is made using impact ground powder.

Spherical beryllium powder has been made by inert gas atomization [17,18] (Fig. 2), centrifugal atomization [19], and by the rotating electrode process [20-22]. This type of powder has only been made in limited quantities. The first two processes involve break up and rapid cooling of a molten metal stream to form powder. Spherical beryllium powder from inert gas atomization is used in the current beryllium plasma spraying program at Los Alamos National Laboratory [19]. The rotating electrode process consists of arc melting the end of a long cast cylinder which is rotating about its axis. Molten droplets of metal are thrown off the end of the rotating cylinder and solidify in flight. This method produces coarser powder than the other two methods; the mean particle size is 200 pm or greater.

Beryllium powder must be consolidated at elevated temperatures to form useful products. Powder consolidation can occur by all the conventional PM consolidation techniques including vacuum hot pressing (VHP), cold pressing (CP) and sintering (S), hot isostatic pressing (HIP), cold isostatic pressing **(CIP) and HIP,** CIP and S, CIP and extrusion, and so on. **VHP and HIP** are the most widely used consolidation routes. Process outlines for **VHP and HIP** are shown in Figs. 3 and 4. Heat treatment is used after consolidation to tailor beryllium properties to structural, aerospace instrument and optical applications. A high temperature heat treatment around 870°C is used to maximize creep resistance and other properties at elevated temperatures. This heat treatment ensures that all low melting point aluminum impurities are contained in a higher melting point beryllium compound, $AlFeBe_4$. The ITER reference grade for plasma facing component applications, S-65C, uses such a heat treatment.

Like other metals, beryllium can be machined and formed by a wide variety of techniques. It has the general machining characteristics of chilled grey cast iron or heat treated aluminum castings [23]. Beryllium can be rolled, extruded, forged, stamped, joggled, and drawn to produce bars, tubes, sheet, plate, wire and other forms [24]. Some of these processes can have a large effect on beryllium mechanical properties as is described below. Heat treatment of beryllium is used to relieve residual stresses from processing and machining.

A glossary of processing terms is given in Appendix A.

4. Effect of processing on fusion relevant properties

Processing can change bulk properties and surface properties of beryllium. Changes in bulk mechanical properties due to machining damage

Table 2

General effect of processing induced texture on beryllium room temperature mechanical properties'

	Ultimate tensile strength (MPa)	Yield Strength (MPa)	Percent elongation
Isotropic HIP block (S-200FH)°			
Longitudinal	438	343	4 6
Transverse	447	346	5 3
Moderately textured VHP block (S-200F)"			
Longitudinal	372	255	4.0
Transverse	393	241	6.0
Strongly textured extrusions'			
Longitudinal (extrusion direction)	745	345	10
Transverse (perpendicular to extrusion direction)	434	372	0.6
Highly textured sheet			
Powder metallurgy sheet, b			
in-plane	483	345	10
Through thickness (out-of-plane)			<1
Ingot metallurgy sheet`			
In-plane	276	138	3
Through thickness (out-of-plane)			<1

" Typical values. NOTE that materials producers will only guarantee minimum specified properties, they will NOT guarantee typical or mean values.

[b] Limited by basal plane cleavage.

Guaranteed minimum values only.

and changes in anisotropy of properties with processing are the two most common concerns for tokamak applications. Surface bombardment and tritium diffusion studies in the laboratory can be influenced by the surface oxide layer, overall oxygen concentration, and surface finish.

4.1. Machining damage

Machining will be used to transform consolidated beryllium into useful shapes for plasma facing component applications. Due to the limited crystallographic slip systems available at room temperature in beryllium, machining produces a very thin damaged surface layer consisting of microcracks, microstructural features called twins, and residual stresses. The thickness of the damaged layer varies with the magnitude of the machining forces, but is typically 0.08-0.13 mm [25]. The damaged surface layer will primarily affect crack sensitive properties such as tensile elongation. In most cases it is possible to completely remove this damaged layer with controlled acid etching. When geometry, size or tolerances of the part do not allow etching, a heat treatment is used to remove microstructural twins and eliminate residual stresses. If the part is not amenable to heat treatment, surface damage can be minimized by finishing the machining sequence with a series of progressively shallower cuts.

Electric discharge machining (EDM) is used to machine small features and complex curved shapes. The castellations or stress raiser grooves used by JET in its beryllium divertor tiles were cut using EDM. The surface damage left by EDM, called an as-cast surface, is thinner than other conventional machining processes, but is still measurable [25,26]. The EDM wire is usually made of a copper based alloy and can leave a thin loosely adherent copper residue on the as-machined surface. A flash etch with nitric acid is used to remove that copper residue. Hashiguchi [26] found that tensile samples with a surface produced by conventional etching of an EDM surface had slightly better tensile properties than tensile samples with an as-EDM surface.

4.2. Control of oxygen levels in beryllium

Oxygen content in beryllium is process dependent. There are two main processing routes to beryllium powder, and the cause of oxygen concentration variation is dramatically different for each of these routes. Each route starts out with vacuum casting of beryllium. At that point there are about 300 ppm oxygen in the beryllium. The first route is chipping of vacuum cast billets to chips and subsequent grinding to powder. The increase in oxygen concentration which occurs in this route is due to oxidation of the beryllium chip surfaces during the energetic grinding processes.

Fig. 7. (a) As-machined S-65C beryllium surface with approximately 90 pin rms surface roughness (b) Same surface after etching to remove machining damage. Note that black horizontal bar in lower right legend shows the scale of 10 pin in the photograph.

There is a clear connection between type of grinding process and oxidation of the powder surface. Impact ground powder tends to have less oxygen content than attrition ground powder. Ball milled powder has been either impact or attrition ground before it is ball milled, and so having gone through two energetic grinding processes has a very high oxygen concentration. The much finer particle size of ball milled powder (less than 10 pin) also has a significantly higher specific surface area which yields a larger volume percent of beryllium oxide.

Gas atomized beryllium (spherical beryllium powder) is made without grinding, so a much lower BeO concentration can be achieved. Beryllium metal stock is put into an induction heating crucible, melted, and poured through a nozzle as a thin liquid cylinder or sheet. High pressure gas jets break up the liquid into fine particles; the break up of the liquid by a gas is called atomization. In beryllium atomization, oxygen is added to the atomization gas to passivate the beryllium powder surface and thereby avoid any rapid exothermic reaction of the fine powder with air after atomization. The oxygen concentration in the resulting fine, spherical beryllium powder is a function of the oxygen content in the melt; and surface oxidation of the molten beryllium droplets by the 1 % oxygen in the atomization gas. Final oxygen content of gas atomized beryllium is about half or less of beryllium made using the grinding processes.

Beryllium bonds very strongly with oxygen, and all oxygen in beryllium is in the form of beryllium oxide (BeO). BeO distribution in consolidated beryllium products is at the surfaces of the impact ground or gas atomized powder particles used.

4.3. Crystallographic constraints on properties and processing

Isotropic properties are achieved for beryllium by use of HIP. However, many other metalworking processes (rolling, extrusion, VHP and so on) produce anisotropic properties. The anisotropy of beryllium properties with crystallographic direction is well documented. A single crystal of beryllium will have very different mechanical

Fig. 8. As-ground *S-65C* beryllium surface with approximately *30* kin rms surface roughness. Note that black horizontal bar in lower right legend shows the scale of 10 [m in the photograph

properties depending on which crystallographic direction is tested. Ductility of beryllium single crystal is virtually zero parallel to the crystallographic c-axis, and can reach 140% along the basal plane in high purity crystals [27]. The limiting factor in beryllium ductility is the ease of cleavage of the basal plane in the hexagonal close packed (hcp) structure; stresses perpendicular to the basal planes are not reduced by slip and cause basal plane cleavage. Fig. 5 shows the location of the basal plane in an hcp unit cell.

Polycrystalline beryllium with fine grain size masks some of the anisotropy of the unit cell. There is an averaging effect whose magnitude depends on how randomly the single crystal grains are oriented. If the grains have a tendency to align their crystallographic planes with each other, the bulk sample is said to be textured. Degree of texturing varies from zero (random distribution of crystallographic axes) to 100%, as shown in Fig. 6. Texture is often measured by the c-axis pole density observed in X-ray diffraction. Highly textured sheet formed from attrited powder has a pole density of 20:1 (J. Marder, private communication). Moderately textured S-65 sheet has a pole density of 4:1-6:1. A pole density of 1:1 or 1:1.5 corresponds to no texture.

Fig. 6 also shows the effect of texturing on anisotropy in room temperature percent elongation. The randomly oriented crystals in the block form (most closely realized by HIP products) give relatively low but uniform average percent elongation in three orthogonal directions. The moderately textured ingot sheet gives higher elongation in the two in-plane directions, but a decreased percent elongation in the through thickness direction. Highly textured PM sheet with virtually all basal planes parallel to the sheet surface shows even higher elongation in the two in-plane directions, but zero elongation in the through thickness direction. Vacuum hot pressed material such as S-65C has texture intermediate between that of HIP material and ingot sheet. As shown in Table 2, other properties measured at room temperature such as ultimate tensile strength and yield strength have a similar relationship to texture as elongation. VHP properties vary depending on how a sample is oriented with respect to the pressing ram: longitudinal is defined as parallel to the ram direction and transverse is defined as perpendicular to the ram direction. Similarly, the longitudinal direction for extrusions is parallel to the direction the extrusion is being pushed and transverse is perpendicular to that. As the table indicates, the most isotropic properties are found with HIP and properties vary with direction for VHP, extrusion, and rolled sheet products. The effects of texture are somewhat ameliorated at elevated temperatures because an increased number of crystallographic slip systems become active.

The fusion community has been interested in whether high purity beryllium has better mechanical properties and high heat flux performance than current commercial grades. A large international effort which studied high purity beryllium showed that there was no change in the two limiting properties, anisotropy of slip and basal plane cleavage, with increasing purity [27]. Critical resolved shear stress is lowered on some slip planes with increasing purity, but this decreases strength without increasing ductility. Fracture stress is not affected by the difference between commercial purity and high purity [28]. Note that overall impurity contents down to 8 ppm were studied.

Table 3

Manufacturer specifications for chemical composition and room temperature tensile properties of commercially available structural

	S-65B/S-65C'	S-200E[b]	S-200Fa	S-200F-H`	S-200F-C[d]
Chemical composition					
Be, min %	99.0	98.0	98 5	98.5	98.5
BeO. max 'Y,,	10	2.0	1.5	1.5	1 5
AI, max ppm	600	1600	1000	1000	1000
C, max ppm	1000	1500	1500	1500	1500
Fe, max ppm	800	1800	1300	1300	1300
Mg, max ppm	600	800	800	800	800
Si, max ppm	600	800	600	600	600
Other max ppm	400	400	400	400	400
Specifications for tensile properties at room temperature					
Ultimate tensile strength (MPa), mm	290	276	324	414	262
Typical-L	372	372	441	317	
Typical-T	397	393	414	262	
0.2% Offset yield strength (MPa) mm	207	207	241	297	172
Typical-L	251	255	345	207	
Typical-T	251	241	345	172	
% Elongation, min	3.0	10	20	3.0	20
Typical-L	3.8	4 0	4 9	4.1	
Typical-T	6.0	6.0	4.9	4 1	

Typical mechanical property values are higher than specifications.

NA, not available

[a] *Impact ground powder, VHP grade. S-65B and S-65C differ only in inspection specifications*

[b] *Impact ground powder, HIP grade.*

[c] *Impact ground powder, CP and S grade*

4.4. Berylliuni surface oxide

In general, the thickness and structure of the surface oxide on beryllium varies with processing history. This has implications for tritium diffusion experiments [29].

Beryllium, like aluminum, has a thin adherent oxide layer. The layer consists of beryllium oxide (BeO). The thickness and morphology of this layer depends on time and temperature, and is therefore process dependent to a large degree. Standard reaction rate kinetics apply to beryllium oxidation, so as time and/or temperature are increased, the thickness of the oxide layer increases. The oxide surface layer adherence is preserved during oxidation in air at temperatures up to 700°C. In that temperature range, oxidation kinetics are dominated by diffusion through the oxide layer and are parabolic [30]. At 700°C, the internal stresses of the oxide coating cause it to crack and even spall off. Oxidation kinetics become linear and the accelerated kinetics is often called breakaway oxidation [30].

Some of the fabrication processes may cause beryllium to come in contact with water. This will also affect oxide thickness and structure. Aqueous corrosion of beryllium is similar to that of aluminum. Beryllium has been used in the high purity water at 100°C for 10 years in the Materials Test Reactor and shown minimal corrosion [31]. This corresponds to a very slow oxide thickness growth rate. However, low concentrations of halide ions or sulfate can produce accelerated corrosion, particularly via pit formation [32]. Aqueous corrosion product tends to be less coherent and less dense than corrosion product formed by gas-solid reaction. As a practical matter, the normal acids and oils in fingerprints will mar a finely machined beryllium surface.

4.5. Effect *of machining on beryllium surface finish*

Surface finish may not necessarily affect beryllium performance in the tokamak, but it does have some relevance to analytical surface studies in fusion. Like many metals, the microscopic roughness of a machined beryllium surface depends on the details of the machining chip formation process. This is a complex heat transfer and stress distribution problem [33,34] which is a function of machining feeds, speeds, lubricants, depth of cut and so on. In machining, welding of the base material to the cutting tool occurs and then forces build up on this welded machining chip to rip it away from the base metal [33,34]. This surface finish can microscopically appear as a series of uninterrupted parallel lines or as parallel lines interrupted by shallow craters depending on the sharpness of the machining tool and the levels of other machining variables [35,36]. The shallow craters are a common response of many metals, including beryllium, to high frictional forces in a given machining parameter space. Beryllium is most commonly finished to a 128 Vin rms surface finish. The best surface finish (around 32 Vin rms) is usually obtained by light grinding. Etching to remove machining damage leaves a surface of very small diameter and shallow overlapping pits. Fig. 7(a) shows an as-machined surface with approximately 90 Vin rms surface roughness and Fig. 7(b) shows the same surface after etching. Fig. 8 shows an as-machined surface with approximately 30 Vin rms surface roughness. These are examples of surface finish and are not necessarily typical because of the wide variation in machining variables which are used.

Table 4

Manufacturer specifications for chemical composition and room temperature tensile properties of commercially available structural beryllium grades

	MSC-100'	SR-200^b
Chemical composition		
Be, min %	99.5	98.0
BeO, max %	< 100 ppm	2.0
Al, max ppm	1000	1600
C, max ppm	1000	1500
Fe, max ppm	1500	1800
Mg, max ppm	NA	800
Si, max ppm	1000	800
Other. max ppm	100	400
Specifications for tensile properties at room temperature		
Ultimate tensile strength (MPa), min	276	483
0.2% Offset yield strength (MPa), min	138	345
% Elongation`, min	3.0	100

Typical mechanical property values are higher than specifications.

NA, not available

a Fully annealed ingot sheet.

Elongation in the plane of the sheet Out-of-plane elongation is significantly lower (<1%)

5. Summary of commercial grades

Although beryllium is used in relatively small quantities compared to steel or aluminum, specific grades have been tailored for the major aerospace applications: structural, guidance instruments and optics. Grain size, impurity content, anisotropy and BeO content are the principal differences between these grades. The properties and degree of characterization vary depending on the needs of the applications. Shown below are examples of various bulk product grades. Extruded beryllium is available from more than one manufacturer.

Structural grades (S-65C, S-200F, S-200E) are processed to provide the best combination of ductility and strength. They are the most versatile grades and are the most well characterized. Note that S-65C is the reference material in ITER for plasma facing component and first wall applications.

Instrument grades (I-220B, 1-400A, 1-70A) are optimized to provide the least distortion in aerospace guidance instruments. They are optimized to provide the best precision elastic limit (PEL), which is the maximum stress which can be applied before one pin of plastic strain is made.

Optical grades (0-50, I-70A, 1-220B) are optimized for reflectivity, thermal expansion and polishing characteristics. The principal application is in satellite mirrors, although there are some ter-

Table 5

Manufacturer specifications for chemical composition and room temperature tensile properties of commercially available instrument and optical beryllium grades

	1-70'	1-70-H [b]	1-220-H [b]	1-250"	1-400`	O-50[b]
Chemical composition						
Be, min	99.0	990	98.0	97.0	940	99.0
BeO. max	0 7	0.7	2 2	2 5	4.25 mm.	0.5
Al, max ppm	700	700	1000	1000	1600	700
C, max ppm	700	700	1500	1500	2500	700
Fe, max ppm	1000	1000	1500	1500	2500	1000
Mg. max ppm	700	700	800	600	800	700
Si, max ppm	700	700	800	600	800	700
Other, max ppm	400	400	400	400	100	400
Specifications for tensile properties at room temperature						
Ultimate tensile strength (MPa), min	241	345	448	517	345	241
Typical-L	NA	503	634	606	NA	NA
Typical-T	NA	490	634	606	NA	NA
0.2% Offset yield strength (MPa), min	172	207	345	448	N S	172
Typical-L	NA	338	542	524	NA	NA
Typical-T	NA	338	542	524	NA	NA
% Elongation, min	2.0	2.0	2 0	1.5	NS	2
Typical-L	NA	5.1	3 7	3.0	NA	NA
Typical-T	NA	5.1	3 7	30	NA	NA
Microyield strength d	12	21	41	69	62	N S

Typical mechanical property values are higher than specifications NS, No specification.

' Impact ground powder, VHP grade. [b] impact ground powder. HIP grade Ball milled powder, VHP grade.

d Stress required to produce first 2.5 x 10-2 ~jm (1 x 10^{-6} in) of permanent strain

restrial mirror applications where weight and infrared reflectivity are important.

Chemical composition and nominal room temperature tensile properties for commercially available beryllium grades are shown in Tables 3-5.

Appendix A. Glossarv of processing terms

This section is meant to provide the reader with those few processing terms which can quickly convey information about anisotropy of properties and product purity. Beryllium is primarily made by PM methods to provide strength in bulk forms, but much of the early characterization work has been done on ingot metallurgy material. A section on PM terms will be followed by a section on ingot metallurgy.

A.1. PM

A.1.1. Grinding

Production of most Be powder begins with chipping of a beryllium ingot. The chips are then ground using one of three grinding methods.

A.1.1.1. Attrition *milling.* Chips are ground into powder between a fixed, grooved beryllium plate and a rotating, grooved beryllium plate. Plate-like particles are produced which tend to align preferentially during powder consolidation steps, resulting in anisotropic mechanical properties. This technique is not presently used in production.

A.]. *1.2. Impact grinding.* Beryllium chips are suspended in a stream of high velocity gas and then directed at a solid beryllium target. The blocky particles produced by the impact result in a less textured microstructure and more uniform properties in all directions than attrition milling. The largest volume of beryllium is made using impact ground powder.

A.]. *1.3. Ball mill grinding.* Ball mill grinding produces extremely fine particles which in turn produce an extremely fine grained microstructure in the final product. This expensive and time consuming method is used to obtain resistance to mechanical distortion in precision guidance components.

A.1.2. Atomifation

Inert gas atomization produces spherical beryllium powder particles in contrast to the angular or blocky particles produced by grinding. Atomized spherical powder (ASP) generally has less than half as much BeO as the other beryllium powders. This technology has only recently been successfully applied by beryllium.

A.1.3. Powder consolidation

The method of powder consolidation has a strong effect on anisotropy of mechanical properties. Cold compaction of powder is either done by CP or CIP. **VHP and HIP** are the two most widely used hot consolidated techniques, although S and powder extrusion are also performed. Plasma spraying of beryllium to form deposits on substrates is presently being developed.

A.1.3.1. CP. Powder is fed into a steel die and then uniaxially pressed from the top and bottom. The cold pressed or green powder billet then goes to one of the hot consolidation processes, usually S. CP tends to yield anisotropic mechanical properties.

A.1.3.2. CIP. Powder is fed into flexible rubber bags which are sealed and lowered into a water filled pressure vessel. Pressure is applied simultaneously from all directions (isostatically). The CIP billet then goes to one of the hot consolidation processes, usually HIP, S or extrusion. Products produced with a CIP step tend to have more isotropic mechanical properties than products produced with a CP step.

A.1.3.3. VHP. Powder is poured into a vertical cylindrical die. Pressure is then applied from rams at the top and bottom of the die under temperature and vacuum. Mechanical properties are anisotropic; mechanical properties measured parallel to the pressing direction (longitudinal) are generally lower than properties measured perpendicular to the pressing direction (transverse).

A.1.3.4. HIP. Loose powder or a CIPed powder billet are placed in a steel can which is welded shut after degassing at elevated temperature. The sealed can is then placed into a pressure vessel where it is heated and then pressed from all directions simultaneously (isostatically) by argon gas. Simple shapes made by HIP have minimal anisotropy in mechanical properties. Complex near net shapes can be made by this technique.

A.1.3.5. Sintering *(S). A* CPed or CIPed billet is placed in a furnace and heated under vacuum. Diffusion of beryllium atoms produces bonding. Sintered products have a coarser grain structure than HIP products and have more anisotropy in mechanical properties.

A.1.3.6. Extrusion. Billets made by CP or CIP are generally used as input stock, although extrusion of loose powder has been done. The feedstock is put in a cylindrical steel can, and degasses at elevated temperatures. The can is then welded shut and heated in a furnace. The hot can is then pushed through a die by a ram. Extruded products have anisotropic properties; the properties in the ram direction (longitudinal) differ from those in material perpendicular to the ram direction (transverse).

A.]. *3. 7. Plasma spraying.* this description covers a wide range of processes which spray molten or semi-molten beryllium droplets onto a substrate where they solidify into a partially dense deposit.

A.2. Ingot metallurgy

A.2.1. Cast

This covers any process where molten beryllium is poured into a mold and solidified by liquid heat transfer or solid heat transfer. Cast beryllium generally has very coarse grain size and a different distribution of BeO compared to PM beryllium. The strength and ductility of cast beryllium is much lower than PM beryllium but can be improved by cold working and hot working it to a fine grain size. Rolling is at present the only practical method to produce a fine grain size in case beryllium. The most pure forms of beryllium are prepared by casting and zone refining techniques.

A.2.2. Ingot sheet

This is beryllium sheet produced from cast beryllium by rolling. It is notable for low BeO content and more ductility in the out of plane direction than PM sheet.

A.3. Refining processes

Beryllium can be refined using the same techniques as other metals, but zone refining and vacuum distillation are most currently used the most.

A.3.1. Zone refining

A bar of beryllium is placed in a device where the furnace moves axially along it. A very small molten zone is formed at one end of the furnace and impurities are driven into the liquid by thermodynamic forces. Very high purity beryllium with very large grain size is produced. There is not a commercial scale facility for beryllium zone refining.

A.3.2. Vacuum distillation

Beryllium is vaporized and separated from impurities by fractional condensation. A high purity, coarse grained product is produced.

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Note:

Handling Aluminum-Beryllium Alloys in solid form poses no special health risk. Like many industrial materials, beryllium-containing materials may pose a health risk if recommended safe handling practices are not followed. Inhalation of airborne beryllium may cause a serious lung disorder in susceptible individuals.

The Occupational Safety and Health Administration (OSHA) has set mandatory limits on occupational respiratory exposures. Read and follow the guidance in the Material Safety Data Sheet (MSDS) before working with this material.

For additional information on safe handling practices or technical data on Aluminum Beryllium Alloys, contact Brush Wellman Inc.

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