UCRL-TR-222539

LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

# Beryllium Manufacturing Processes

A. Goldberg

June 30, 2006

This work was performed under the auspices of the U.S. Department of Energy by University of California, Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

# BERYLLIUM MANUFACTURING PROCESSES

Alfred Goldberg

One of a Series of Reports on Beryllium

October 15, 2005

Lawrence Livermore National Laboratory, Livermore, CA 94551

This Effort funded by the Weapons System Engineering
Certification Campaign (C6)

# Table of Contents

# Beryllium Manufacturing Processes

## I. 1ntroduction

This report is one of a number of reports that will be combined into a handbook on beryllium. Each report covers a specific topic. To-date, the following reports have been published:

- Consolidation and Grades of Beryllium
- Mechanical Properties of Beryllium and the Factors Affecting these Properties
- Corrosion and Corrosion Protection of Beryllium
- Joining of Beryllium
- Atomic, Crystal, Elastic, Thermal, Nuclear, and other Properties of Beryllium
- Beryllium Coating (Deposition) Processes and the Influence of Processing Parameters on Properties and Microstructure

The conventional method of using ingot-cast material is unsuitable for manufacturing a beryllium product. Beryllium is a highly reactive metal with a high melting point, making it susceptible to react with mold-wall materials forming beryllium compounds (BeO, etc.) that become entrapped in the solidified metal. In addition, the grain size is excessively large, being 50 to 100 μm in diameter, while grain sizes of 15 μm or less are required to meet acceptable strength and ductility requirements.[1,2] Attempts at refining the as-cast-grain size have been unsuccessful. Because of the large grain size and limited slip systems, the casting will invariably crack during a hot-working step, which is an important step in the microstructural-refining process.[2] The high reactivity of beryllium together with its high viscosity (even with substantial superheat) also makes it an unsuitable candidate for precision casting.[1,3]

In order to overcome these problems, alternative methods have been developed for the manufacturing of beryllium. The vast majority of these methods involve the use of beryllium powders. The powders are consolidated under pressure in vacuum at an elevated temperature to produce vacuum hot-pressed (VHP) blocks[a] and vacuum hot-isostatic-pressed (HIP) forms and billets. The blocks (typically cylindrical), which are produced over a wide range of sizes (up to183 cm dia. by 61 cm high), may be cut or machined into parts or be thermomechanically processed to develop the desired microstructure, properties, and shapes. Vacuum hot-isostatic pressing and cold-isostatic pressing (CIP) followed by sintering and possibly by a final HIP'ing (CIP/Sinter/HIP) are important in their use for the production of near net-shaped parts. For the same starting powder, a HIP'ed product will have less anisotropy than that obtained for a VHP'ed product. A schematic presentation illustrating the difference between VHP'ing and HIP'ing is shown in Figure I-1.[1] The types of powders and the various beryllium grades produced from the consolidated powders and their ambient-temperature mechanical properties were presented in the consolidation report referred to above. Elevated-temperature properties and the effect of processing variables on mechanical properties are described in the mechanical properties report. Beryllium can also be deposited as coatings as well as freestanding forms. The microstructure, properties, and various methods used that are related to the deposition of beryllium are discussed in the report on beryllium coatings.

---

[a] The term "block," in contrast to billet, is associated with the vacuum-hot-pressed product.

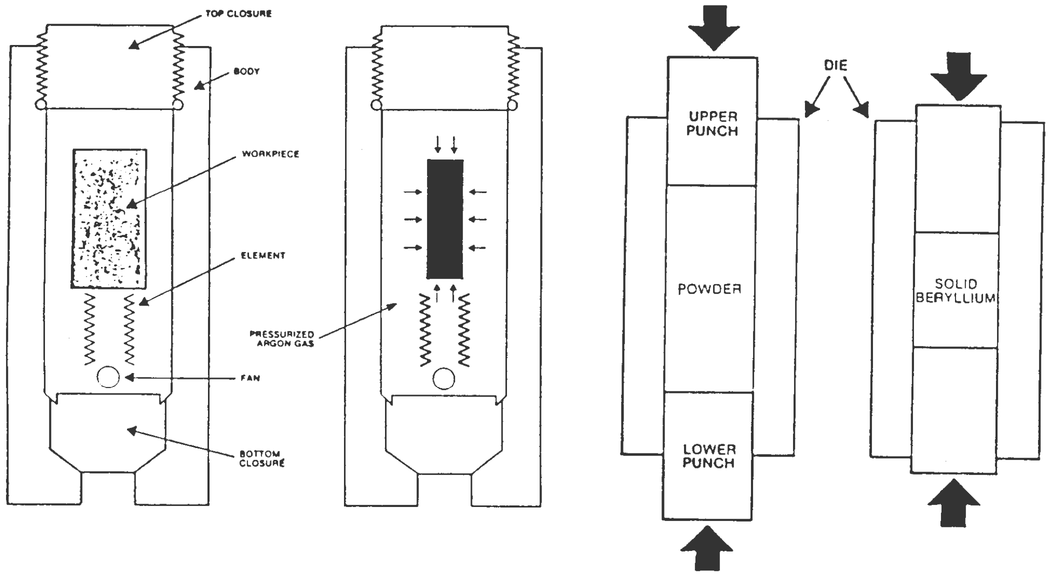


Figure I-1. Schematic illustration of two beryllium-consolidation process: Left—hot isostatic pressing (HIP); Right – vacuum hot pressing (VHP).[1]

Briefly, the beryllium ores are chemically processed into beryllium hydroxide, which is then converted into beryllium fluoride. The fluoride is then made to react with magnesium in a high-temperature furnace, forming beryllium fluoride and beryllium "pebbles" (roughly spherical nodules) of 1 to 2 cm in diameter. The beryllium pebbles are somewhat impure, containing a number of high-vapor-pressure elements from the prior reduction processes. The contaminants are removed by induction-vacuum melting and cast into ingots, typically weighing 400 pounds. The ingots are cut into chips in a lathe with a multi-head cutting tool, cleaned, and reduced to the powders used in the consolidation processes.[1] Chemical compositions of two common grades of powders are given in Table I-1.[4]

**Table I-1. Nominal Compositions of Nuclear and Structural Grades of Beryllium Powders.[4]**

| Element or oxide | Nuclear grade S-65C | Structural grade S-200F | Element or oxide | Nuclear grade S-65C | Structural grade S-200F |
|---|---|---|---|---|---|
| Be assay* | 99.0 | 98.0-98.5 | Pb | 0.002 | ---- |
| BeO | 1.0 | 1.5 | Li | 0.0003 | ---- |
| Al | 0.60 | 0.10 | Mg | 0.0006 | 0.08 |
| B | 0.0002 | ---- | Mn | 0.012 | ---- |
| Cd | 0.0002 | ---- | Mo | 0.002 | ---- |
| Ca | 0.01 | ---- | Ni | 0.02 | ---- |
| C | 0.10 | 0.15 | N | 0.02 | ---- |
| Cr | 0.01 | ---- | Si | 0.06 | 0.06 |
| Co | 0.0005 | ---- | Ag | 0.0010 | ---- |
| Cu | 0.015 | ---- | Others** | ---- | 0.04 |
| Fe | 0.0800 | 0.13 | | | |

*Indicates maximum content; minimum contents are given for remainder of elements. ** Indicates other metal impurities.

Powders are formed by ball milling, disk grinding, or impact grinding the chips or by an inert-gas atomizing process (gas-pressure spray). Depending upon the method used, the powder particles differ mainly in their shape. Gas-atomized powders are spherical and isotropic and have excellent flow and packing characteristics.[b] The properties of the consolidated materials made with these powders are equal or superior to the properties obtained with those made with comparable mechanically produced powders.[5] In mechanical attrition, especially at the low impact-collision rates that occur within a ball mill, slip and fracture of the (brittle) beryllium chips proceed primarily along basal planes of the hexagonal closed-packed crystal structure, yielding plate-like particles. During the vibratory loading of the VHP chamber, the flat fracture surfaces tend to become aligned perpendicular to the loading direction and thereby impart anisotropic properties to the hot-pressed billet. Of the various attrition methods employed, the degree of anisotropy is smallest using the impact process, in which a high-velocity-gas stream propels the chips against a beryllium target. The high impact force causes the beryllium chips to fracture on other planes in addition to the basal planes resulting in blocky-like particles, which have a lowered tendency to align during loading of the powder. A reduction in the degree of anisotropy leads to improved overall ductility. Consequently, impact grinding had become the major mechanical-production method for producing beryllium powders. Less anisotropy is obtained under isostatic loading (HIP'ing) than under uniaxial loading (VHP'ing). The minimization of anisotropic properties in beryllium is an important factor when used in control and diagnostic systems, especially if involved with optics.

**Table I-2. Comparison of Properties of Beryllium with Other Materials.[6]**

| Material | Modulus-to density ratio, $10^8$ in | Density, ρ, lbs/in$^3$ | Young's Modulus, E, $10^6$ psi | Thermal conductivity, K, BTU-ft/ (h-ft$^2$-$^O$F) | Specific heat, C, BTU/ lb/ $^O$F | CTE, $10^{-6}$ in/in/ $^O$F | Thermal Stabilizing Factor sec/in$^2$ | Natural frequency factor |
|---|---|---|---|---|---|---|---|---|
| Beryllium | 6.6 | 0.067 | 44.0 | I04 | 0.46 | 6.5 | 1.5 x $10^{-4}$ | 25.0 |
| Aluminum | 1.1 | 0.098 | 10.5 | 128 | 0.22 | 12.5 | 0.9 x $10^{-4}$ | 10.5 |
| Titanium | 1.0 | 0.160 | 16.0 | 4.5 | 0.13 | 5.0 | 23 x $10^{-4}$ | 10.0 |
| Steel | 1.0 | 0.290 | 29.0 | 27 | 0.12 | 6.0 | 6.4x $10^{-4}$ | 10.0 |
| Optical Dielectric | 1.6 | 0.090 | 14.5 | 0.92 | 0.22 | 0.2 | 110 x $10^{-4}$ | 12.0 |

Thermal-stabilizing-time factor = (ρ x C)/(2 x K), sec/ in$^2$; Natural frequency factor = $\sqrt{(E/\rho)}/1000$.

Table I-2, which compares a number of properties of beryllium with those of some competitive materials, was developed to illustrate the advantages offered by beryllium.[6] Applications for beryllium, which were reported in a review paper published in 2000,[2] and others[7] include fusion- and fission- nuclear reactors, infrared-target-acquisition systems, inertial-guidance systems, space telescopes, satellite structures, optics for space and ground–base systems, commercial optical scanners, audio components, high-speed-computer parts, avionics thermal management, windows for x-ray sources and detectors, missile-guidance systems, structural material for solar-energy collectors, and fire-control systems for tanks.

This report deals with various processing methods used to manufacture a beryllium product: rolling, forging, swaging, extruding, stretch forming, deep drawing, spinning, three-roll forming, wire drawing, near net-shape forming, machining, adhesive bonding and mechanical fastening. Other joining methods such as welding and brazing are discussed in the report on joining.

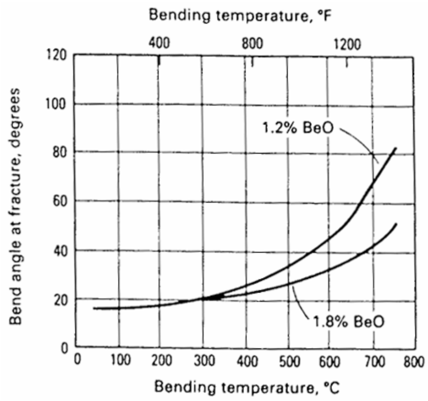
---

[b] In gas atomizing a stream of molten metal is broken into droplets by a jet of high-pressure gas. Surface tension causes the droplets to form into spheres before they solidify.

## II. Producing and Forming Wrought Products

The consolidated beryllium powders can be processed into various basic wrought shapes using conventional methods with the appropriate safeguards for handling beryllium and for protection against atmospheric attack. Sheet and plate have been shaped, bent, stretched, spun, deep drawn, joggled, shear formed, stamped, and drawn using both reduction and bending techniques.[8, 9] Associated with its hexagonal close-packed-crystal structure and limited slip systems, beryllium has limited formability. Accordingly, it should generally be formed at elevated temperatures, typically in the range 540 to 815$^{O}$C, and at slow speeds. The optimum temperature range for forming was given as between 600 and 750$^{O}$C[8] and above 700$^{O}$C.[9] Other factors affecting its formability are composition and prior thermomechanical history; for example the ductility of vacuum-hot-pressed block can be improved by hot working.[10] The iron-to-aluminum ratio must be controlled to prevent hot shortness[c] due to aluminum precipitating along the grain boundaries.

The effect of temperature on formability in terms of bend angle at fracture is illustrated in Figure II-1.[10] The figure also shows that the BeO content can have a significant effect on formability. The author points out that the data were generated when beryllium sheet material had a guaranteed elongation of 10%, which was subsequently increased to values between 15 and 20%. Accordingly, the two curves would now be shifted to higher bend angles. An example showing the effect of temperature on the bend ratio, r/t. is presented in Figure II-2.[9] Since beryllium is strain-rate sensitive, the forming rate should be kept as low as possible. An example of the effect of strain rate on formability is illustrated in Figure II-3, which shows that for a given thickness, smaller bend radii or for a given radius, larger thicknesses are attainable at the slower bending speed.[10] It appears that the two slow-rate and high-rate curves would tend to merge at the higher temperatures. Figure II-4 gives the forming speed as a function of the minimum bend ratio, r/t.[9] It was reported that ingot-derived rolling stock has better formability and weldability, primarily due to its lower oxide content, compared to stock derived from consolidated powders.[5] Using ultrahigh-purity, zone-refined, ingot-source beryllium, rolling reductions of 90% were achieved at 200$^{O}$C.[8] A microstructure consisting of small equiaxed grains is also important for formability.



---

[c] Hot shortness refers to a metal being brittle at an elevated temperature (where hot working operations would normally be performed). It is due to the presence of continuous grain-boundary films of a low-melting constituent. (See report on "Mechanical Properties of Beryllium and Factors Affecting these Properties" for detailed discussion of this problem.)

Figure II-1. Effect of BeO content on bend angle to fracture as a function of temperature of beryllium sheet using a 2t-bend radius.[10]

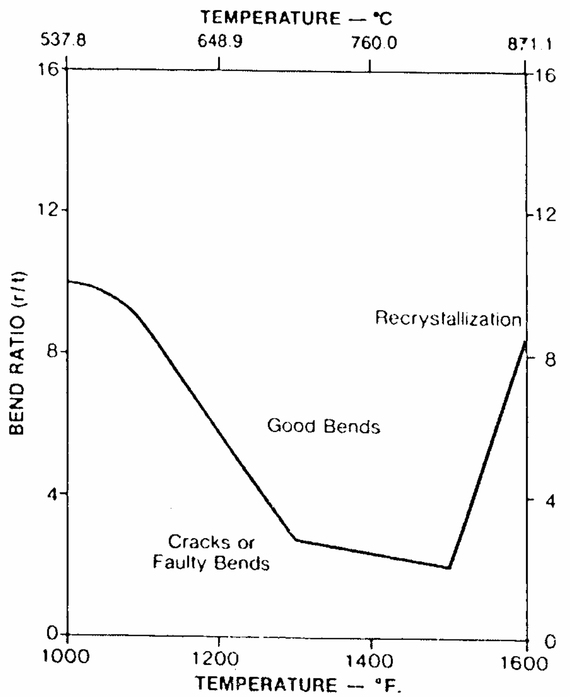


Figure II-2. Minimum bend ratio (radius/thickness) as a function of temperature for cross-rolled 2.03-mm-thick- beryllium sheet.[9]

Forming practices should include etching the sheet prior to forming and, where appropriate, heating the dies to the metal temperature. Due to the abrasiveness of beryllium, inserting stainless-steel foil or mild-steel foil at drag places between the beryllium and die is recommended. Oxide films that may have formed can be removed by either liquid honing or polishing with a fine abrasive material.[9]

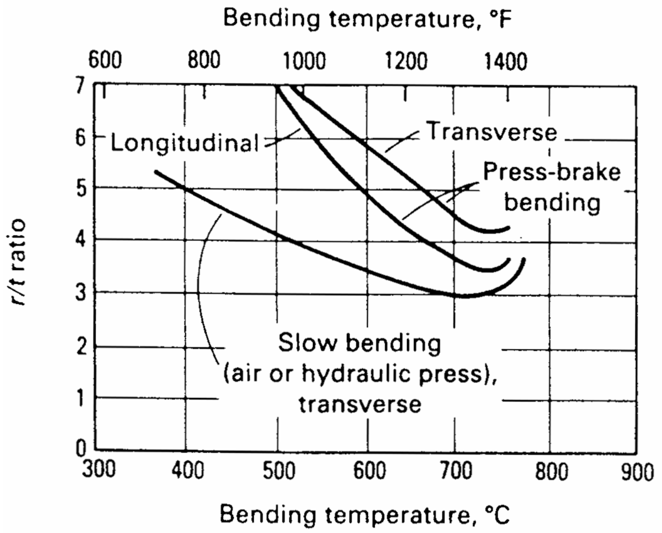


Figure II-3. Minimum bending limits (radius/thickness) of beryllium sheet as a function of temperature, comparing press-brake bending with relatively slow (air or hydraulic) press bending.[10]

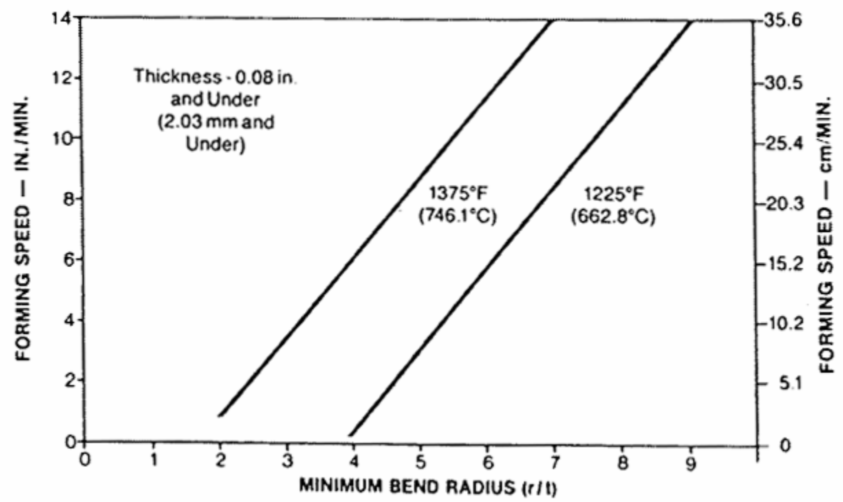


Figure II-4. Recommended maximum forming speed as a function of bend ratio (radius/thickness) for cross-rolled 2.03-mm-thick beryllium sheet.[9]

## II-1. Flat-Rolled Products

Flat-rolled products, such as plates, sheets, and foils, are generally produced by encasing the beryllium in steel jackets and rolling, usually, at a moderately elevated temperature. Flat-rolled stock 0.508 mm thick or less is referred to as foil, between 0.508 mm and 6.35 mm as sheet, and greater than 6.35 mm as plate. Sheet produced by rolling vacuum-hot-pressed (VHP) block (referred to at times as powder sheet to distinguish it from ingot-produced sheet) is characterized by fine grain sizes. (about10 µm), high BeO content (about 2%), strong texture, high strength and ductility in the plane of the sheet, and fair formability at elevated temperatures. By contrast, sheet rolled from cast-ingot stock exhibits a coarse grain size (about 50 µm), a low BeO content (about 50 ppm), weak texture, moderate strength and ductility, and excellent formability at elevated temperatures.[11] Rolling (as well as upsetting) beryllium tends to align the basal planes parallel to the rolled plane and in the direction of rolling. This alignment of basal planes results in anisotropic properties providing increased ductility along the rolling plane with a corresponding reduced ductility in the thickness direction. Cross rolling (alternating by 90 degrees the direction of rolling the beryllium) is used if uniform biaxial properties are required.[9]

The specified grade numbers for sheet and plate are SR-200 and PR-200, respectively. Their chemical composition conforms to that of the VHP block S-200F. Ambient-temperature tensile properties in the plane of the sheet or plate and the maximum sizes available are shown in Table II-1-1.[9] The rolled sheet and strip were made by cross rolling billets of VHP block encased in steel. The relationship of shear strength to tensile strength was reported as being higher than that for most materials at the lower temperature range and lower than expected at temperatures exceeding 482°C.

**Table II-1-1 Tensile Properties and Sizes Available for Warm-Rolled Beryllium Sheet and Plate.[9]**

| Thickness, in. (mm) | Grade | Minimum UTS, MPa | Minimum YS, 0.2% Offset, MPa | Minimum Elong.,% | Maximum size available, cm |
|---|---|---|---|---|---|
| 0.021-0.030 (0.533-0.762) | SR-200 | 482.6 | 344.7 | 10 | 61 x 183 |
| 0.031-0.125 (0.763-3.175) | SR-200 | 482.6 | 344.7 | 10 | 61 x 213 |
| 0.126-0.250 (3.176-6.350) | SR-200 | 482.6 | 344.7 | 10 | 61 x 168 |
| 0.251-0.450 (6.351-11.430) | PR-200 | 448.2 | 310.3 | 4 | 61 x 127 |
| 0.451-0.600 (11.431-15.240) | PR-200 | 413.7 | 275.8 | 3 | 61 x 102 |

A study on powder-metallurgy sheets[d] describes hot-rolling a slab, machined from VHP block.[11] The slab was rolled at 650 to $900^0$C with reheats in a furnace to maintain temperature. After rolling, the steel jackets were removed by shearing. The sheet was then flattened and stress relieved between large ceramic plates. Certain large sizes required rejacketing of the beryllium. Sheet sizes as large as 91 x 244 cm were made. Some sizes available (1979) commercially were: 2 mm x 1.2 m x 4.6 m, 4 mm x 1.2 m x 4.6 m, and 1.3 cm x 0.8 m x 1.3 m .

Mechanical properties for cross-rolled 2.5-mm-thick sheet of SR-200E (VHP) beryllium were reported by NASA/JSC.[12] Tensile, biaxial, and shear tests were performed and the results were compared to the results based on several finite-element models. Table II-1-2 shows the tensile results obtained and compared with results reported by other sources. Some of the tensile sheet specimens that were sanded (not included in the table) showed extensive degradation in the properties. The elongations became limited to about 1%; the UTS dropped about 16 and 20 % in the transverse and longitudinal directions, respectively; by contrast, the yield strengths were not significantly affected by the sanding. The degradation depended on the coarseness of the papers (280 and 400 grit).

**Table II-1-2 Comparison of Tensile Results in the Longitudinal and Transverse Directions for Beryllium Cross-Rolled Sheet.[12]**

| Source and Material | Orient. | YTS, MPa | UTS, MPa | Elong., % |
|---|---|---|---|---|
| NASA/JCS (1991)<br>SR-200 (2.54 mm thick) | L[a]<br>T | 392<br>415 | 517<br>497 | 17.3<br>25.2 |
| Kovarik (1984)<br>SR-200E (0.51 to 1.19 mm) | L[b]<br>T[b] | 393<br>400 | n/a<br>n/a | n/a<br>n/a |
| Marder (1986)<br>SR-200E (0.53 to 0.64 mm) | L[c]<br>T[c] | 345<br>345 | 483<br>483 | 10<br>10 |
| MIL-HDBK-5E (1987)<br>SR-200D (1.78 to 6.35 mm) | Lc<br>T | 296<br>296 | 448<br>448 | 5<br>5 |
| Fenn, etal. (1967)<br>S-200 (1.96 mm) | L<br>T | 372<br>386 | 538<br>552 | 16<br>16 |
| Ingels (1966)<br>(0.51 to 3.05 mm) | L<br>T | 352—434<br>345—421 | 538—586<br>483—593 | 10—24<br>7—25 |

---

[d] The use of “powder” in powder sheet is conventional with beryllium usage. It refers to the sheet originating from powder in contrast to originating from ingot. The latter would then be referred as ingot sheet.

[a] Average of three tests; [b] Average of 12 tests; [c] Minimum design properties

Procedures used in rolling a machined cast ingot (billet), canned in stainless steel, were described as follows:[11] The edges of the billet were chamfered to prevent the beryllium from contaminating the weld during the canning process. It was then cleaned and vacuum baked at 600$^{O}$C. A parting compound was applied to all billet faces to prevent bonding to the can during rolling. The can was gas-tungsten-arc-welded at several places along each edge and final closure was performed using electron-beam welding. A 9-cm-thick billet was reduced to 0.5 cm using 21 rolling passes with cross rolling (90$^{O}$rotation after each pass) from pass 8 through 17. Ten reheats were made, starting at 980$^{O}$C after pass 4 and dropping in steps to 790$^{O}$C after pass 20. The major problems encountered in prior runs were achieving breakdown of the non-uniform, coarse cast structure and the curling of the can and the beryllium during rolling. Lowering the breakdown-rolling temperature too early resulted in a mixture of cast and refined structures, while too high a final temperature resulted in excessive grain growth. Curling during rolling can result in cracking of the beryllium sheet as well as rupturing the can, which will permit the ingress of air, ruining the sheet. The rolling parameters that affected the various problems encountered were listed as: billet temperature, reduction per pass, number of passes between reheats, reheat conditions, lubrication of rolls, crown of rolls, and surface finish of rolls.[11] The first three affect the microstructure. The last three affect curling problems; for example, lightly lubricating the top roll while maintaining the bottom roll dry will favor a slight downward curl. Difference in roll-surface roughness also caused curling.

Bare rolling (not canned) of ingot material has been performed on a production scale.[11] A specially designed in-line furnace with doors at both ends and mounted on the roll tables allows direct transfer of the machined beryllium billet (or sheets) from furnace to rolls. Preheating and intermediate reheats were performed in an inert-atmosphere annealing furnace held at 790$^{O}$C. The beryllium was then transferred to the in-line furnace held at 730$^{O}$C in an inert atmosphere. The rolled material was finally vacuum annealed for 4 to 6 hours at 760$^{O}$C. Billets up to 46 cm wide x 0.5 cm thick were rolled, the initial dimensions depending upon the goal for the final sheet dimensions. A hot-flattening procedure was used if curling occurred between any passes, which was required when cross rolling. A combination of can rolling and bare rolling was found to be successful, whereby the final pass or passes are performed bare after removal of the can. The mechanical properties, surface finish, and thickness uniformity of the bare-rolled sheets were superior to those of the can-rolled sheets. Typical mechanical properties of bare-rolled, ingot-source beryllium are listed in Table II-1-3.[9]

**Table II-1-3. Typical Mechanical Properties of Bare-Rolled, Ingot-Source Beryllium.[9]**

| Thickness, mm | UTS, MPa | Yield strength, 0.2% offset, MPa | Elong., % | Typical size, cm | Test direction |
|---|---|---|---|---|---|
| 1.52 | 301 | 182 | 5.0 | 30.5 x 107 | Transverse |
| | 343 | 182 | 6.1 | | Longitudinal |
| 2.54 | 308 | 182 | 4.9 | 46 x 132 | Transverse |
| | 343 | 182 | 6.2 | | Longitudinal |
| 3.81 | 280 | 182 | 3.5 | 36 x 107 | Transverse |
| | 301 | 175 | 5.0 | | Longitudinal |
| 5.08 | 252 | 175 | 3.0 | 36 x 107 | Transverse |
| | 273 | 175 | 4.0 | | Longitudinal |
| 8.25 | 231 | 182 | 2.7 | 74 x 74 | Transverse |

| | | | | | |
|---|---|---|---|---|---|
| | 245 | 182 | 2.5 | | Longitudinal |

Foils are usually made by rolling at elevated temperatures in steel cans. As beryllium cannot be successfully rolled at room temperature, a cold-rolled surface is not available.[9] Due to its use primarily as windows for detector and source applications, which involve special characteristics, close tolerances, and reproducibility, foils are only available in two high-purity grades: PF-60 and IF-1.[9] Their chemical compositions are listed in Table II-1-4. Krivko et al., produced beryllium foil by hot rolling plates of beryllium condensate contained in sheaths (proprietary details were not given).[13] A fine-grained substructure was developed with a UTS of about 475 MPa and a yield strength at 0.2% offset of about 395 MPa. Annealing for one hour at temperatures up to 550°C increased the ductility with practically no change in either microstructure or strength. Beryllium foils have been used for domes in loudspeakers. Foils were rolled down from slabs. To obtain sufficient ductility and formability, the foils had to be formed above 300°C. The foils were formed in an hermetically sealed heat-forming chamber.

Foils ranging from 25 to 250 µm thick were produced by bare rolling on laboratory-type mills starting with bare-rolled, 1-mm-thick sheets.[11] The thinner foils were chemically milled to size after reaching rolled thicknesses of about 200 to 250 µm. Attempts at rolling down to 75 µm resulted in a loss of over 75% of material. The high-loss rate was attributed to embrittlement by surface oxidation, edge cracking due to springback and deformation of the rolls, and heat loss and chilling effect on transfer to the rolls. Rolled-and-etched sheets, 15 cm x 23 cm x 25 µm thick were produced, but only had isolated areas (10 cm$^2$) that were free of pin holes. High purity beryllium should be used to obtain leak-tight, 25-µm foil. Beryllium foil is available in thicknesses from 0.025 to 0.5 mm in panel sizes up to 125 x 300 mm.[4]

**Table II-1-4 Chemical Composition of Beryllium Foils[9]**

| **Composition** | **Grade** | |
|---|---|---|
| | IF-1 | PF-60 |
| Beryllium , %Min. | 99.8 | 99 |
| BeO, %Max. | 0.03 | 0.8 |
| Al, ppm Max. | 100 | 500 |
| B | 3 | 3 |
| Cd | 2 | 2 |
| Ca | 200 | 100 |
| C | 300 | 700 |
| Cr | 25 | 100 |
| Co | 5 | 10 |
| Cu | 50 | 100 |
| Fe | 300 | 700 |
| Pb | 5 | 20 |
| Li | — | 3 |
| Mg | 60 | 500 |
| Mn | 30 | 120 |
| Mo | 10 | 20 |
| Ni | 200 | 200 |
| N | — | 400 |
| Si | 100 | 400 |
| Ag | 5 | 10 |
| Ti | 10 | — |
| Zn | 100 | — |
| Available Gauge | 0.0003-0.02 in (0.008-0.508 mm) | 0.0003-0.125 in (0.008-3.175mm) |

Although ingots are generally considered too brittle to be worked, very small vacuum-cast ingots having fine grains can be rolled into foils. Successful rolling of high-purity, bare-ingot sheet from 5 to 8 mm down to 1 mm by preheating for 1 h at 790 ± 14°C in an inert atmosphere and then rolling at 730 ± 14°C at a 10 to 16% reduction per pass was reported[14]. Room-temperature tensile properties were reported as 175 MPa yield strength, 230 MPa ultimate strength, and 3 to 5% elongation. At thicknesses less than 2 mm, the frequency of edge cracking was increased and special handling was required to prevent heat losses at the edges. The ingots were produced using electrolytic-flake beryllium yielding a very high-purity, fine-grained product. This process, which was initially developed to make foil for beryllium windows, was not commercially available at that time (1986). The author stated that by applying special thermomechanical treatments to ingot-processed (high-purity) beryllium, he was able to produce low-oxide products with equiaxed-grain sizes of less than 30 μm. With these small grain sizes, grain-boundary sliding was obtained at room temperature, thus providing an additional deformation mode; ductilities as high as 7% with strengths in the range of 250 to 300 MPa were possible. Charpy-impact values of 4 to 6 J have been reported, which are close to the values obtained for 7075-T6 Al alloy. By contrast, conventional hot-pressed billets have a Charpy-impact value of 0.7 J.[14]

## II-2. Extrusions

Extrusion methods are important for producing long shapes, both simple and complex. Extrusions can be produced with consistent mechanical properties and within commercial tolerances. They are typically used in the aerospace and satellite applications. Directional properties are developed depending on the degree of the crystallographic anisotropy. Input billets for extrusions are usually machined hot-pressed blocks. Unsintered pressed billets can also be extruded. The extrusion billets are jacketed in low-carbon-steel cans with shaped nose plugs and are hot extruded through a steel die between 900 and 1065°C. Warm extrusions are produced at 400 to 450 °C. Steel jackets are chemically removed from the beryllium.[4] Beryllium powders can also be extruded.[15] A schematic for canned extrusion of beryllium is shown in Figure II-2-1.[16] A soft "cutoff" block such as graphite or copper, which is also extruded, is placed between the beryllium and steel dummy block and is cut at the end of a run. This avoids the need to remove the toxic beryllium from the dummy block at the end of a run. Warm extrusions are also produced bare using very low extrusion speeds, low reduction ratios, and special solid-film lubricants that strongly adhere to the billet. The main advantage is the ability to produce small complex shapes with very good dimensional control.[16]

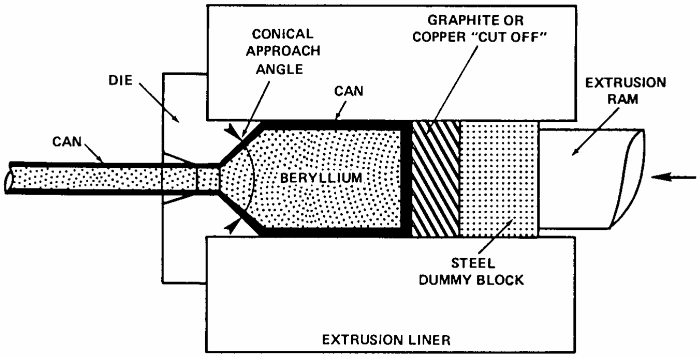


Figure II-2-1. Schematic illustration for canned extrusion of beryllium.[16]

Canning overcomes beryllium's strong tendency to gall or stick to the extrusion tools. Furthermore, if not canned, abrasive oxides that score tooling would form at the elevated temperatures (above 600°C). Also, because of the coarse-grained structure in the cast ingot, and the differences in the crystallographic orientation of individual grains relative to the extrusion direction, a significant difference in deformation behavior may occur in different regions of the billet. Carbon steel is the preferred canning material. It has approximately the same extrusion constant (flow resistance) as beryllium at extrusion temperatures; it does not form low melting eutectics with beryllium below 1165°C; it has relatively low solubility in beryllium (0.9 at% at 1000°C, decreasing rapidly with decreasing temperature); it has reasonable lubricity; it does not stick to tools; and it can be removed from the beryllium by pickling in nitric acid.[16] A conical-approach-extrusion die (Figure II-2-1), good lubrication, tightly fitting tools, and avoidance of the formation of a skull (shell) in the extrusion liner provide the streamlined-metal flow that is necessary for extrusion of beryllium. Dies for beryllium extrusion differ mainly from conventional dies by the requirement of a conical approach to the die aperture. For complex shapes, the approach must be sculptured, shaping it with special attention so as to promote the flow of the canning material into areas where the can may become extremely thin.

Extrusion temperatures for beryllium range between 840 and 1066°C. Temperatures at the lower end of this range are preferred as higher strengths are then attainable since the lower temperatures would produce finer grain sizes. Reduction ratios should be above 9:1and not exceed 60:1. Low reduction ratios may not develop required properties, while high reductions may lead to excessive alloying between can and beryllium due to self-heating.[16] The pressure required to produce streamlined flow is given by the following expressure:

$$P = K \ln R,$$

where P is the pressure, R is the reduction ratio ( cross section of billet/cross section of extrusion), and K is the extrusion constant. The constant represents resistance to deformation and is based on past experience for a specific temperature. It can be used as a guide for a specific operating condition for simple shapes. The value of K will vary with temperature, type of material, extrusion shape, and operating parameters. The dependence of the extrusion constant on temperature is shown in Figure II-2-2 for a number of materials. The operating parameters and extrusion shapes were not given.[16]

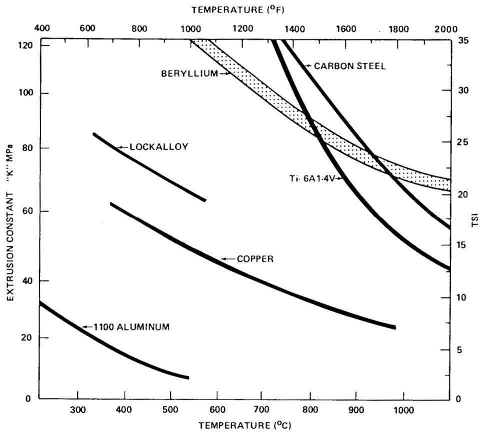


Figure II-2-2. Extrusion constant, K, as a function of temperature for beryllium and other related materials.[16]

With the development of canning, the three available forms of beryllium—cast, loose powder, and consolidated powder—can be extruded. Because of the large grains, combined with the pronounced crystalline anisotropy of cast beryllium, rough, bark-like surfaces are developed in canned-extruded beryllium obtained from castings. Unless heavily worked (high reduction ratios) during the compression part of the deformation, extrusions may be susceptible to grain-boundary cracking. Such cracking can be minimized by using high-purity beryllium. Extrusions made from consolidated powders, having finer grain sizes, have much smoother surfaces than those formed from cast material. When extruding loose powder, the powder has to be compressed before metal is issued from the die. During this stage, the powder form shortens, which could lead to development of folds in the can, thus producing a defective product. This problem was avoided by having the charge increased to 60% of theoretical density prior to canning. Densification from the pour density (30%) to 60% was done in the can in stepwise layers using appropriate precautions of not contaminating the powder with can material.[16] Most extrusions are made from high-density, vacuum-hot-pressed billets. The use of such billets as starting stock avoids the problems associated with extrusion of cast material or loose powders.

Cans are usually made from US 16 gage (1.6 mm) tubing. Heavier cans up to 6 mm thick may be required due to uneven distribution of the can encasing noncircular shapes. The use of the heavier cans could lead to some loss of dimensional control. Using tubing, two end plugs are welded to the filled tubing, the front (nose) plug being cone shaped and the back plug being a disk. The can is usually tightly sealed and evacuated or it can intentionally be incompletely welded. In the latter case some surface oxidation appears during heating that appears to minimize alloying between the steel and beryllium.[16]

Large differences in mechanical properties are obtained between the directions perpendicular and parallel to the extrusion direction. Increased reduction ratios leads to increased degrees of preferred orientation of the basal plane being parallel to the extrusion direction. Although the longitudinal yield and ultimate strengths may increase significantly, they are only increased moderately or even may decrease in the transverse direction, depending on the degree of preferred orientation that is obtained. Elongations would increase in the longitudinal direction and decrease in the transverse direction. An example of such property differences is illustrated in Table II-2-1.[9, 16] A claim was made that up to 20% ductility can be reliably obtained with beryllium extrusions made from commercial-purity-powder billets.[16]

**Table II-2-1. Extruded Beryllium Tensile Properties.[9, 16]**

| **Material** | | **Longitudinal** | | | **Transverse** | | |
|---|---|---|---|---|---|---|---|
| Shape | Diameter cm | Yield, MPa | UTS, MPa | Elong., % | Yield, MPa | UTS, MPa | Elong., % |
| Rod[a] | 2.54-6.35 | 345 | 745 | 10 | 372 | 434 | 0.6 |
| Rod[a] | 0.95-1.27 | 414 | 765 | 10 | ---- | ---- | ---- |
| Tubing[a] | 16.5 OD-9.40 ID | 352 | 655 | 13 | 324 | 414 | 0.7 |
| Tubing[a] | 3.05 OD-2.03 ID | 434 | 800 | 9 | ---- | ---- | ---- |
| Tubing[b] | ------ | 345 | 448 | 5.0 | 207 | 310 | 0.75 |

[a] First four shapes reported for S-200; typical values are listed.[9]

[b] Grade and size are not reported, values indicated are minimum values.[16]

The effect of reduction ratio on the room-temperature tensile properties of a VHP beryllium, warm-extruded at 425°C and annealed at 750 °C, is shown in Figure II-2-3.[17] The data were published in a review paper in 1954.[17] A large early increase in strength was obtained with increasing reductions with a peak elongation of about 10% at an extrusion ratio of about 2:1. Figures II-2-4 and II-2-5 show the effect of temperature on strength and elongation, respectively, for VHP beryllium that was hot extruded between 1050 and 1100°C to three different relatively high reductions.[17] Although there is a three-fold difference in reduction between the highest (38:1) and lowest reduction (12.4:1), the ultimate tensile strength appears to be affected only slightly by this difference in reduction. At the low temperatures, the strength increased and ductility decreased with increased hot-extruded reductions. Reversals on the effect of the amount of reduction on both strength and elongation occurred as the temperature increased. The authors state that "it is not clear why this should occur as the reversals take place at temperatures considerably below the recrystallization temperature[e], which is above 1000°C for beryllium." Furthermore, the reversal along the strength (350°C) and elongation (200°C) curves takes place at different temperatures.

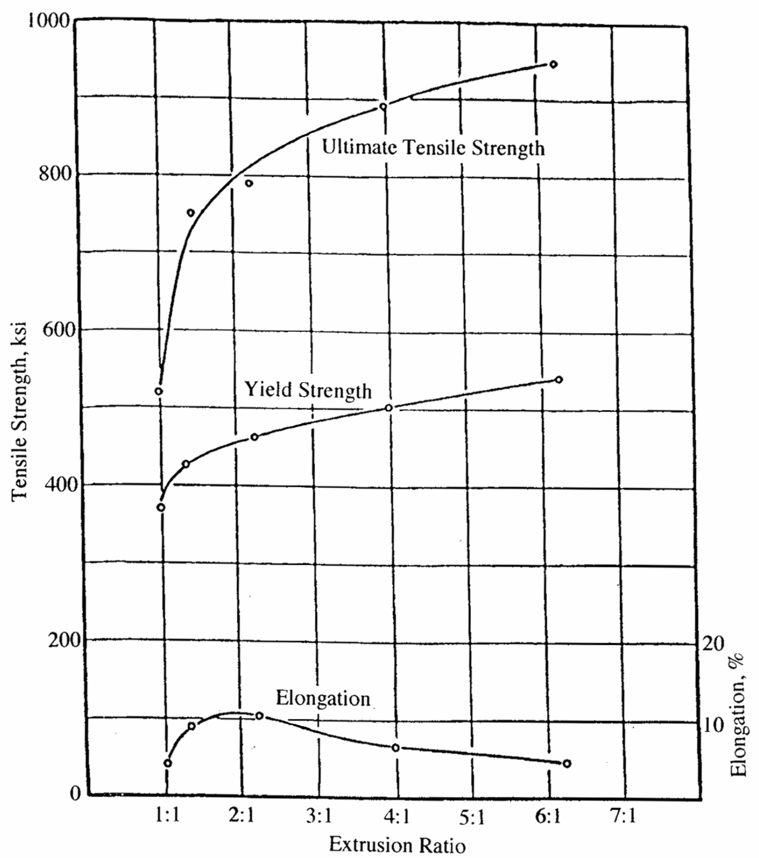


Figure II-2-3 Effect of extrusion-reduction ratio on the tensile properties of VHP (QMV) beryllium warm extruded at 425°C and annealed.[17]

---

[e] The Metals Handbook indicates the recrystallization temperature for beryllium as between 725 and 900°C, depending on the amount of cold work and annealing time, and the hot-working temperature as from 800 to 1100 °C.[18] In addition, the recrystallization temperature would be affected by the type and content of impurities.

Comparisons between the transverse and longitudinal ultimate-tensile strengths and elongations of the hot-extruded VHP beryllium as a function of temperature are shown in Figures II-2-6 and II-2-7. Curves A and B were obtained from comparable beryllium extrusions, while the C Curves were obtained from a coarse-grained material of lower strength.[17] The large differences in strength seen at room temperature gradually decrease with increasing temperature. The data merge at about 450°C indicating that the influence of preferred orientation disappears at elevated temperatures. Similar behavior was shown for the warm extruded condition. The convergence of longitudinal and transverse properties is the result of additional slip systems beginning to operate with increasing temperature. Convergence of the elongation also occurs, however, to a lesser degree than that exhibited by the ultimate tensile strength. It is interesting to note that the peak in elongation at about 250°C, which is frequently observed, only occurs for the longitudinal direction (Curve A). A small ductility peak occurs in the transverse direction (Curve C) for the coarser-grained material at 500°C; this temperature roughly corresponds to where a rapid drop off in strength is initiated.

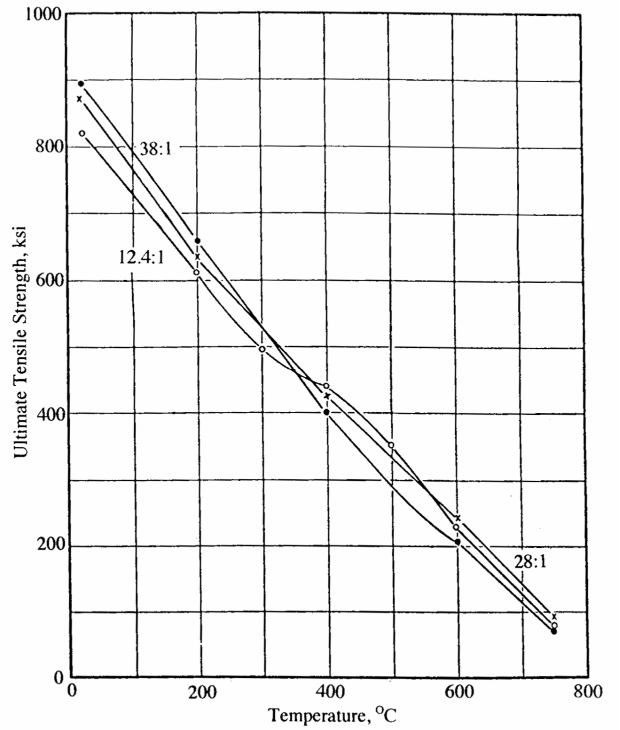


Figure II-2-4. Effect of extrusion -reduction ratio (12.4:1, 28:1, 38:1) on the ultimate tensile strength as a function temperature for VHP (QMV) beryllium hot extruded between 1050 and 1100°C.[17]

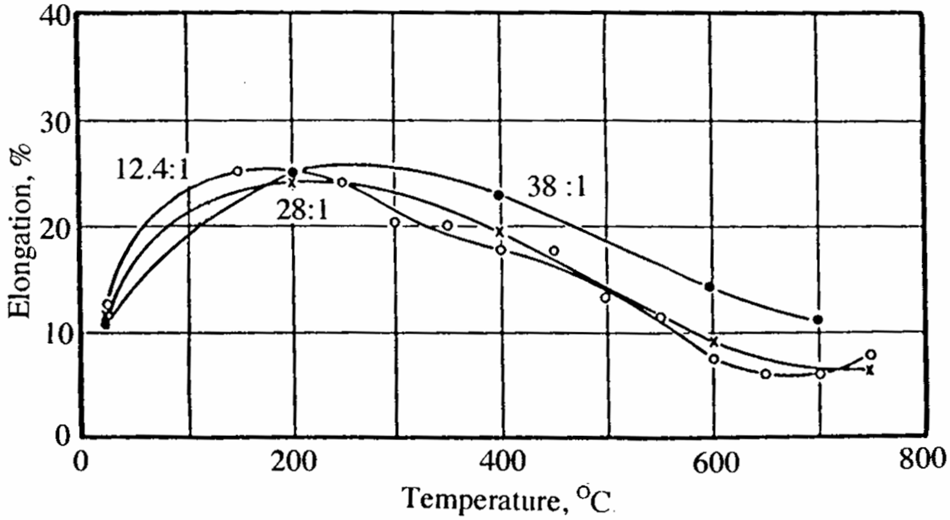


Figure II-2-5 Effect of extrusion-reduction ratio (12.4:1, 28:1, 38:1) on the elongation as a function of temperature for VHP (QMV) beryllium hot extruded between 1050 and 1100°C.[17]

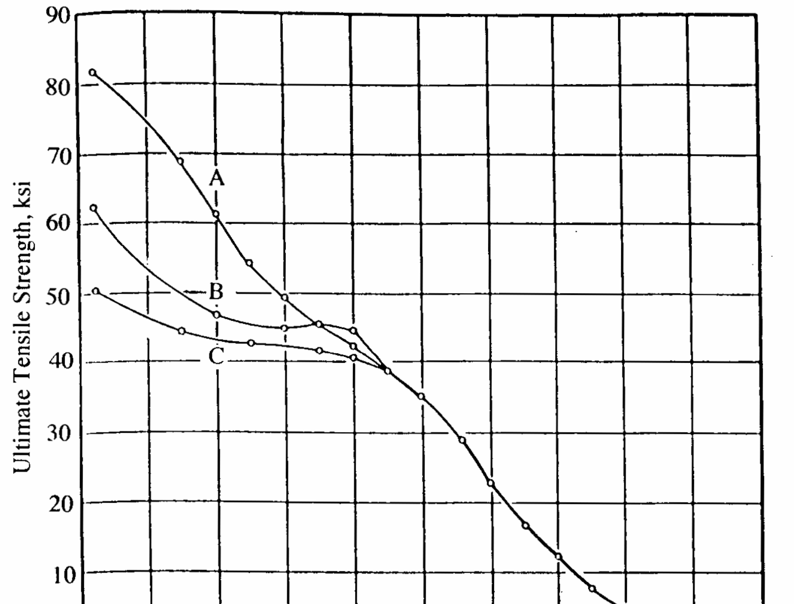


Figure II-2-6. Comparison of longitudinal and transverse ultimate-tensile strength as a function of temperature of VHP (QMV) beryllium hot-extruded at 1050°C. Curves A (longitudinal) and B (transverse) are for comparable beryllium extrusions; Curve C (transverse) was obtained for a coarser-grained, lower-strength extruded beryllium.[17]

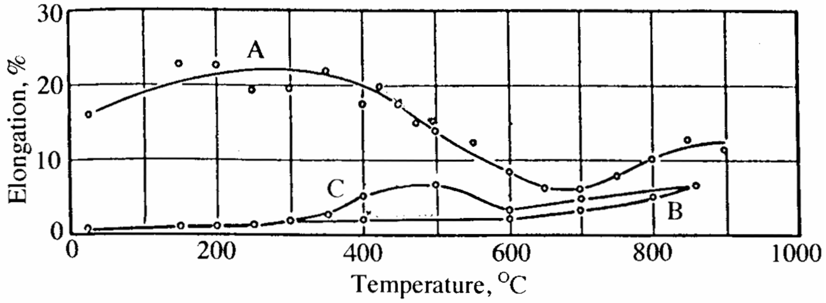


Figure II-2-7. Comparison of longitudinal and transverse elongations as a function of temperature for VHP (QMV) beryllium hot-extruded at 1050°C Curves A (longitudinal) and B (transverse) are for comparable beryllium extrusions; the C (transverse) curve was obtained for a coarser-grained, lower-strength extruded beryllium.[17]

## II-3. Deep drawing

Deep drawing thin-walled beryllium parts can realize considerable savings over the cost of machining.[8, 10] Deep drawing, also referred to as cupping, involves both deep drawing and stretching deformations. A successful deep-drawing operation involves proper control of friction and hold-down pressure, which is affected by the die design and lubricant selection. Lubrication is required to prevent galling between the beryllium workpiece and the die; and, the lubricant film must be maintained along the contact areas throughout the entire draw. Due to the elevated temperatures that are required (above 595°C for the workpiece and 400 to 500 °C for the die), conventional lubricants will burn off. Self-lubricating dies or an overlay of a colloidal suspension of graphite on an asbestos–paper carrier have been successfully used for deep drawing of small parts. Organic emulsified suspensions of powdered aluminum, graphite, or copper can be applied to the draw ring to improve lubricity of the drawing surface under the graphite-impregnated paper. The location of the lubricated asbestos paper on the workpiece blank in a double-action tool for deep drawing of beryllium is pointed out in Figure II-3-1.[8, 10] The double-action provides a restraint on the workpiece (blank or preform) to prevent wrinkling, which may occur when using a single-action tool. The restraint is applied by the blank holder and is developed by a lower (additional) ram in the hydraulic press. Both the holder and punch are supported by a set of cushion pins. The die is connected to the main ram, which lowers down over the punch, pushing the blank holder down and drawing the blank over the punch. The draw ring minimizes the transfer of heat from the blank to the blank holder and acts as stripper to remove the part from the punch. The tooling, however does not provide for an ejector to remove the part from the die. A modified version of the design does provide a part ejector.[8] Restraint is required if the blank is too thin to support itself during the early stages of drawing; excessive thinness causes the blank to buckle and/or wrinkle.

The two most important factors that determine the need for restraint are blank diameter-to-thickness ratio, d/t, and the amount of reduction, R (diameter change/initial diameter), per draw. An increase in either d/t or R will increase the need for restraint. For wall thicknesses greater than 6.35 mm, the value of d should correspond to the average diameter (midway between outer and inner diameters).[8] The safe reduction (formability) limits, R, as a function of d/t for both with and without blank restraint are shown in Figure II-3-2. A safety limit at about 48% is indicated, with the values decreasing with d/t greater than 150 for blank restraint and greater than about 40 for no restraint. If reductions greater than the safety limits are made, then partial drawings with intermediate anneals would be required; however, failure may still occur. It is best to design with dies for several stages of reduction.[8]

Figure II-3-3 shows a cross section of an early single-action design in which restraint was not applied. This design was used for investigations on forming thick-walled beryllium hemispheres. Failure with this type of design can be high because of unfavorable stress distributions and difficulty in lubricating the draw ring[f].[8] Deep drawing of simple hemispherical shells are done at punch speeds from 760 to 1270 mm/min.[10] The primary cause of failure in deep-drawn shapes was observed to be due to localized tensile strains induced by stresses from the punch. The strains are most severe in the early stages of the draw when the contact areas are small. [8] In order to minimize this problem, a conical die was developed to reduce the magnitude of localized stresses by increasing the distribution of the maximum stress over a larger area of the drawing blank. A cross section of the design is shown in Figure II-3-4, in which the blank is supported by the outermost edge of the conical die. Such support introduces a bending mode, requiring less force, especially during the early stages of drawing. A reduction of 20% in drawing forces was achieved using this design.[8] Lubrication of the die was achieved by applying a layer of asbestos paper impregnated with a colloidal suspension of graphite on the drawing surface.

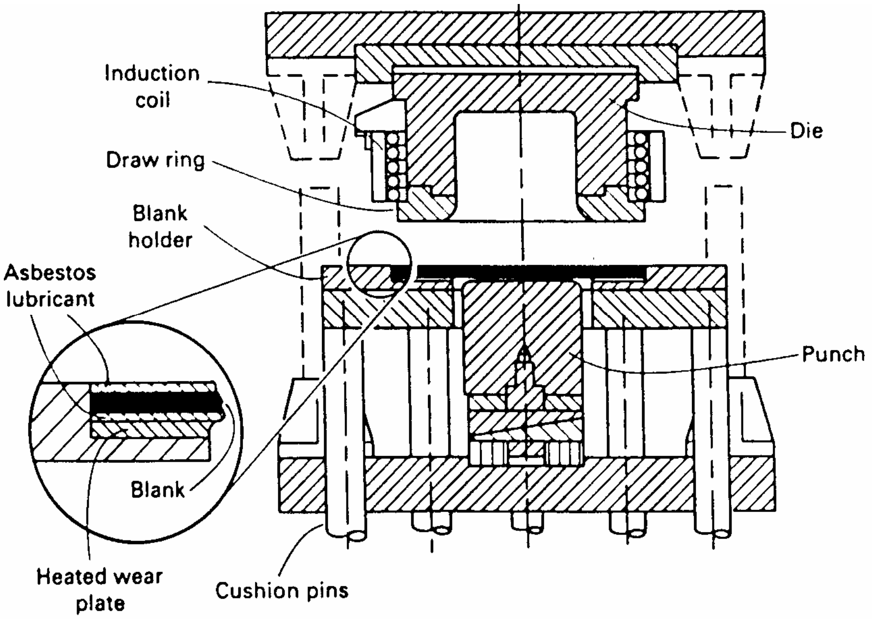


Figure II-3-1. A double-action tool for deep drawing of Beryllium that employs the action of the lower-press action for blank restraint. Lubrication is shown as using asbestos paper impregnated with colloidal graphite as seen in the inset.[8, 10]

---

[f] A draw ring is a ring-shaped die over which the inner edge of a sheet metal is drawn by the punch.

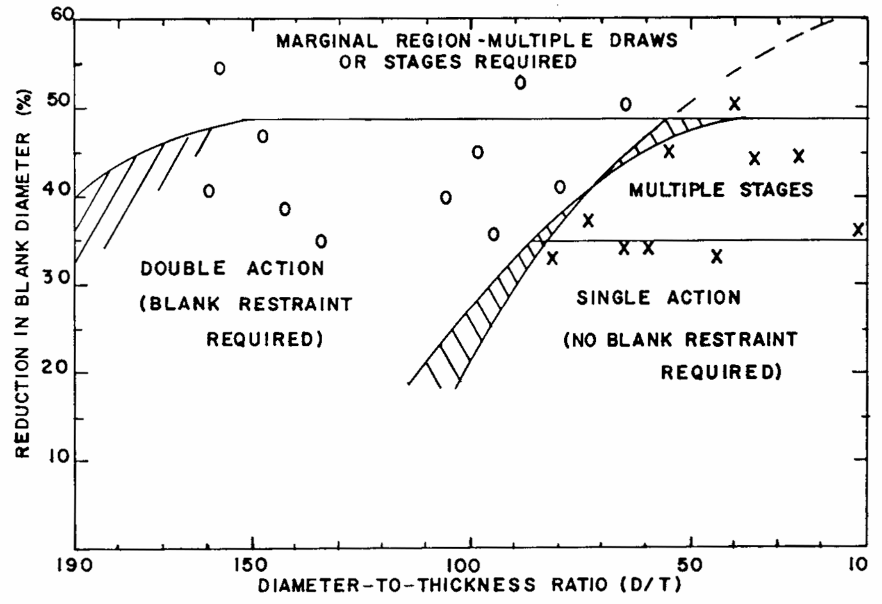


Figure II-3-2. Graphic relationship between reduction and diameter-to-thickness ratio showing the limits for deep drawing cylindrical beryllium shells. The x and o symbols represent experimental data. Shaded areas are marginal.[8]

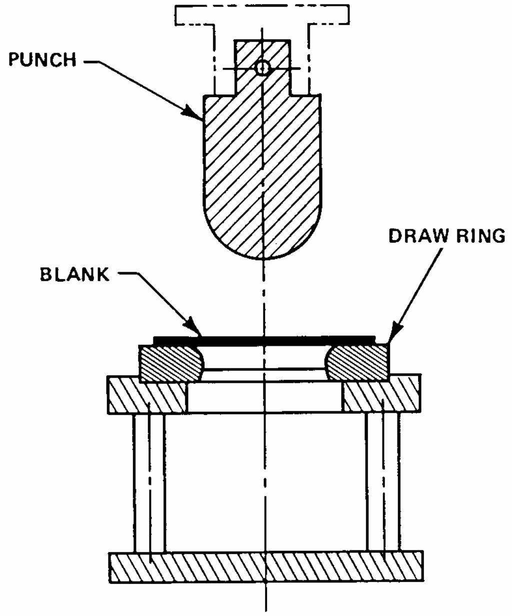


Figure II-3-3. Cross-section view of a simple, single-action punch and draw ring used for deep drawing beryllium.[8]

An overlay method was developed for deep drawing foil parts. A material having similar formability as beryllium is placed on or both on and under (sandwiching) the beryllium until the desired (safe) d/t ratio is achieved as indicated in Figure II-3-2. This material is then discarded after the drawing operation.[y]

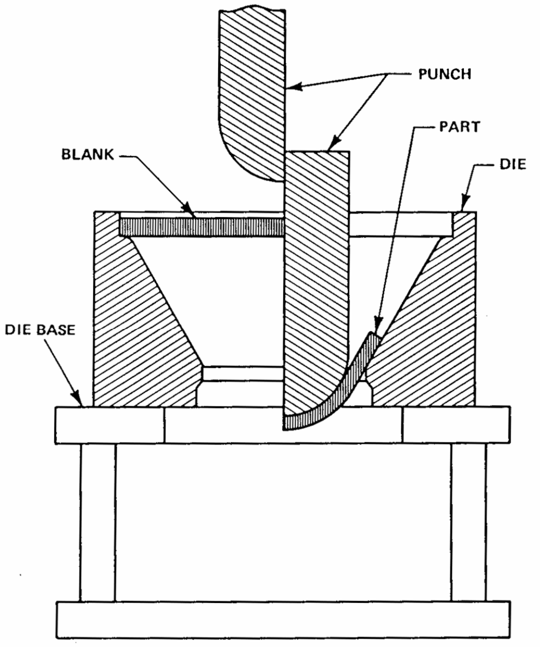


Figure II-3-4. A cross-section view of a conical die used to deep draw a thick-walled hemishell of beryllium. Left side shows the die punch with blank in place before forming the part. The right side shows the formed part just prior to exiting the die.[8]

In designing the tools, adequate clearance between punch and die must be considered. Thickening in the flange in a deep-drawn part may be as much as 22% for a simple hemishell. Common design practice for parts with a straight section is to allow for 20% blank thickening at the equator and to add a two-degree taper to the straight portion of the die above the equator.[8] Cup-shaped parts that require a slightly thicker wall at the equator than at the pole are suited to be formed by deep drawing.

Powder-source (VHP or HIP) beryllium is usually formed between 600 and 650$^{O}$C, independent of blank size or thickness. The temperature for deep drawing ingot-source material depends to a large extent on grain size, as the grain size influences formability. Since the grain size is largely dependent on the degree of rolling reduction used in producing the sheet from which the blank is obtained, it follows that the drawing temperature can be related to the blank thickness. Larger sections will also require more heat because of the thickness. Thicknesses up to 2.54 mm require temperatures between 650 and 700 $^{O}$C. Thicknesses up to 6.35mm require temperatures up to 750 $^{O}$C. Thicknesses up to 8.255 mm have been successfully drawn at 780 $^{O}$C.[8] Tools may be heated by several methods such as torch, resistance, induction, etc., with induction being the preferred method.

Strain rates may vary widely depending on the severity of the draw. For deep drawing simple hemishells, punch speeds between 760 and 1270 mm/min. are typically used. Where optimum conditions of die clearance and lubrication exist, strain rates in excess of 2500 mm/min have yielded successful deep draws.[8] One would expect that blank thickness would be a factor on limiting the speed.

## II-4. Forging

Forging involves shaping a material by impact using forging hammers, or by pressure in forging machines (presses). It can be done with open dies, closed dies, isothermally, at slow rates, and at high rates. Because of its strain-rate sensitivity, however, forging of beryllium is more amenable to the use of presses rather than hammers in that slower rates are obtained with presses. Related processes include radial forging, ring rolling, roll forging, rotary forging, and swaging[g]. The material being forged must have the capability to be deformed without fracturing. The brittle characteristics inherent in beryllium would make beryllium a difficult candidate for swaging One type of test suggested for evaluating the forgeability of beryllium consists of forging a right-circular cylinder with rounded edges and a height-to-diameter ratio of unity. If it can be forged to a height reduction of 60%, the material should be forgeable for making special shapes.[14] To avoid excessive preferred orientation, the amount of deformation should also be limited to 60%. Reductions less than 40% are preferred. Parts forged from HIP'ed materials show less anisotropy than those forged from VHP materials. The various pressing methods (VHP, HIP, CIP) now used to consolidate powders might be considered as pressure forging. These methods confine the metal in closed-die systems under essentially compressive conditions.

Forging would usually be performed between 700 and 760$^{O}$C, which was claimed to be at or slightly below the recrystallization temperature of beryllium.[19] It is also the temperature range where beryllium oxidizes at a slow enough rate to avoid the need for having elaborate safety measures against toxicity of BeO. Higher forging temperatures can be used for billets encased in steel jackets with thicknesses depending on the forging parameters. When encased, billets are forged at temperatures between 760 and 1065$^{O}$C. Forging can be more readily accomplished by maintaining the part in a compressive mode. The necessary restraint can be achieved by: 1) using expandable support rings, 2) appropriate design of the dies, and 3) controlled forging procedures or 4) using a welded steel jacket alone. When using a steel jacket, the billet must be of a shape so that it will be subjected to high restraint throughout the forging cycle.[19]

The early forging studies were performed on beryllium that were canned in mild-steel containers in order to minimize tensile stresses, prevent forging tears, and overcome the brittleness problem. Procedures used were somewhat analogous to those employed in making vacuum hot-pressed (VHP) block, namely fill the container with powder, then degass, preheat to 538 $^{O}$C, seal, and finally heat the container to 982$^{O}$C (typically heated to between 870 and 1040 $^{O}$C) prior to forging. Compacting the powder, as was done with hot-pressed block, was not always performed. To ensure uniform flow of the beryllium and to minimize failure of the can, a high-temperature lubricant should be applied between the can and die surfaces. A schematic of the setup before and after forging is shown in Figure II-4-1.[20] A significant development of contour is illustrated. After forging, the steel container would be removed by machining or acid pickling. Mechanical properties obtained by powder forging, however, were inferior to those developed by forging a solid preform or billet. For example, the yield and ultimate tensile strengths of a powder-forged bowl were about 260 and 425 MPa, respectively, with elongations of about 6.5%.[20] Yield and ultimate tensile strengths developed by forging a solid material are typically

---

[g] Swaging refers to a progressive reduction in cross section area (and corresponding lengthening) by the rapid impact of a revolving pair of mating dies in a swaging machine as the part progresses along the dies. Dies can be changed in the forging machine as necessary for further reduction of the part or a series of machines with successively smaller die radii can be used.

over 350 and 550 MPa, respectively. However, usually the higher strengths are usually associated with reduced elongations.

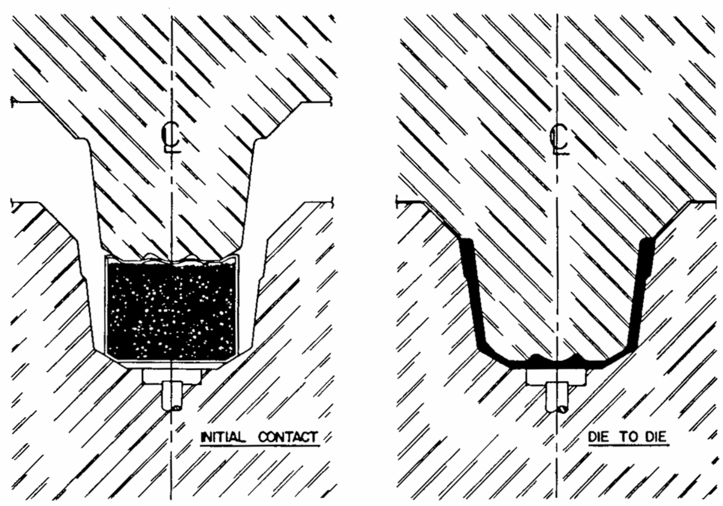


Figure II-4-1. Schematic illustration of forging canned powder. Left side shows canned powder prior to being forged. Right side shows forged part with can prior to removal from die.[20]

Cladding was used in ring-roll forming, primarily to prevent forging tears. This was accomplished by rolling the beryllium against the cladding, so that the beryllium was kept under compressive stresses. The preform consisted of a pre-machined, VHP hollow cylinder. Forging temperatures were between 790 and 850$^{O}$C. The process was used to manufacture 788-mm-diameter x 330-mm-high, Minuteman spacer shells.[20]

Because of the costs involved in can or clad forging, development efforts were directed more towards bare forging. In particular, efforts were focused on developing methods for reducing tensile stresses during forging and producing more forgeable grades of VHP beryllium. Tooling was designed to choke the advancing flow of material in solid forgings, which had been a frequent cause of rupture. A different technique had to be developed for producing hollow shapes where significant flow of metal occurs when there is inadequate die-cavity restraint. Compressive restraint was introduced by placing a hot, mild-steel-expandable-compression ring over the forging punch as illustrated in Figure II-4-2.[20] As the punch (A) is forced into the beryllium preform (B), which sits in the die cavity, the restraint of the compression ring (C) superimposes compressive stresses on the tensile stresses generated by the deforming metal. The steel ring is forced out of the die cavity by the back extrusion of the beryllium and deforms under the head of the die punch. Depending on the required constraint, the steel ring may be heated to a maximum temperature of 1093 $^{O}$C. The expandable-ring-restraint principle can be used by forging in two stages, as illustrated in FigureII-4-3.[19] Another example was described as follows: In the first stage, a solid cylinder, with the die contour providing some choke restraint, is forged into the die cavity to produce the external configuration. In the second stage, the forged solid is back-extruded to develop a hollow using the compressive-ring restraint technique. A hollow cylinder with a tapered flat end was forged at 700$^{O}$C by this two-stage operation. If one of the stages had involved forward extrusion, cladding of the beryllium would have been required for that part of the operation.[20]

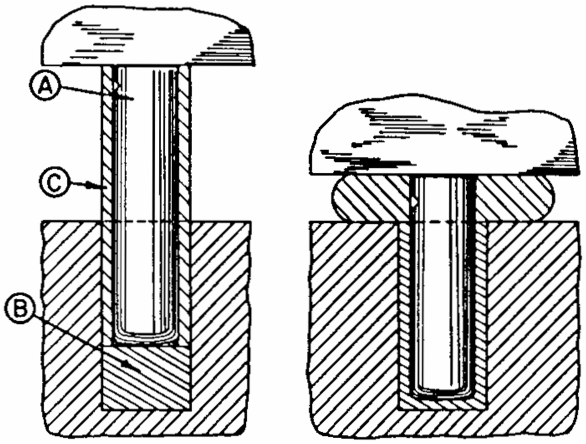


Figure II-4-2. Schematic illustration of hydrodynamic compressive restraint provided by a deformable ring. A—die punch, B—workpiece, C—deformable restraint ring. Left is before and right is after forging.[20]

In addition to cracks being attributed directly to the forging process, cracks may arise due to “die chill” (hot metal shrinking on contacting the cold unheated die) and during extraction from the dies as a result of the high stresses developed from the prior shrinking of the hot metal. Isothermal forging would eliminate the die-chill problem. Proper forging lubrication will reduce any tendency for cracking of the workpiece, which can result from poor metal flow or galling of the dies. The workpiece may be etched in a $3\%H_2SO_4$-$3\%H_3PO_4$ acid solution and coated with a low-temperature, glass-frit-enamel lubricant. When additional forging operations are required, the cleaning and lubrication procedures would be repeated.

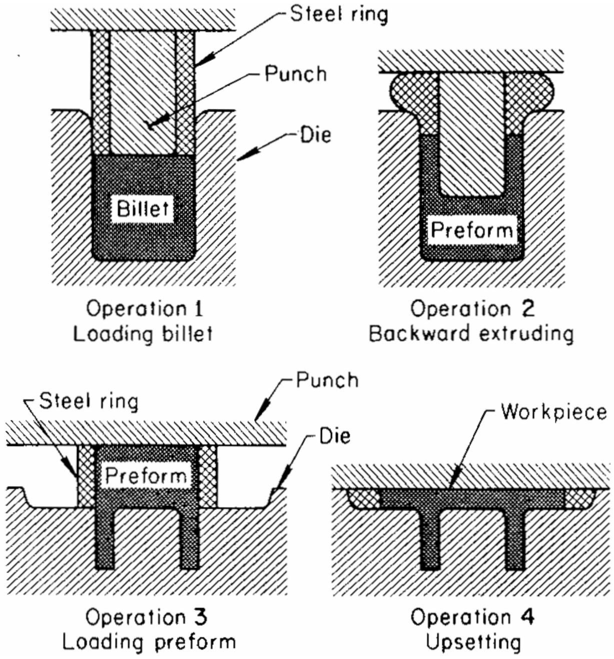


Figure II-4-3. Backward extruding and upset forging of a beryllium partusing a deformable steel ring to support the billet during forging.[19]

As with any of the forming processes, unidirectional forging can lead to significant anisotropy. The term “triaxial” forging was introduced for procedures aimed at either reducing the degree of anisotropy or developing preferred directional properties, where maximum strength or ductility is required in only one direction. This may involve developing a preferred orientation in the preform, redundant forging, upset forging, reversing metal flow during forging sequences, and/or intermittent heat treating.[20] Figure II-4-4 illustrates the effect of three different forging procedures on the properties of beryllium cones forged from VHP S-200.[21] Ten forging sequences were used in each case. One involved back extrusion and forming; another involved upsetting, back extrusion, and forming; and the third involved forward extrusion, upsetting, back extrusion, and forming. An optimum combination of properties for both circumferential and axial directions is obtained for the third option.

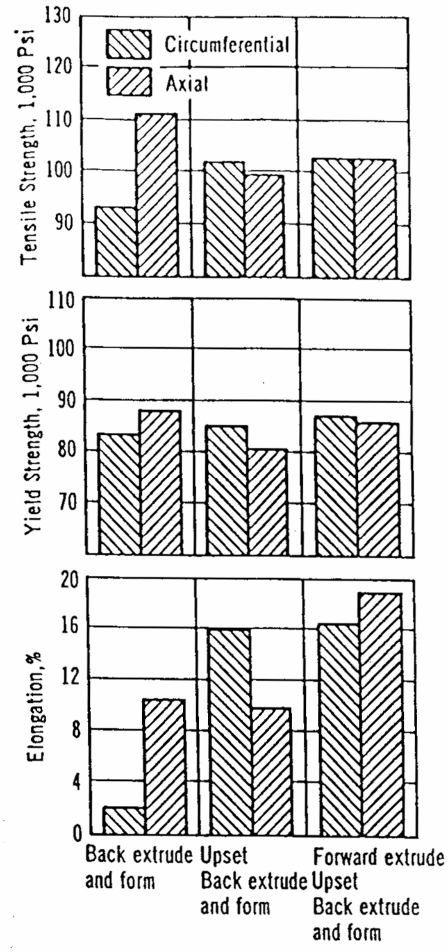


Figure II-4-4.The influence of forging combinations on mechanical properties of forged beryllium cones.[21]

## II-5. Spinning

Spinning involves forming sheet metal or tubing into seamless, circular shapes (hollow cylinders, hemispheres, cones, domes, etc.) by a combination of rotation and force. The forming can be done by either manual spinning or by power spinning. Manual spinning results in no appreciable thinning and involves relatively little force. It is normally done on a lathe and consists of pressing a spinning tool against a circular sheet (blank) that is forced against a shaped mandrel, which is attached to and rotated by the headstock. The workpiece is clamped to the mandrel by a follower block that is attached to the tail stock. Two spinning setups are illustrated in Figure II-5-

1.[22] Simple shapes, where dimensional tolerances are not critical, may not require a mandrel.[22] In power (shear) spinning, the metal is intentionally thinned by shear forces. Spin forming can generally be performed without heating the metal. Exceptions are for metals having low ductilities such as beryllium and for large-thickness blanks used with power spinning. Because of low tooling costs, manual spinning is often used for prototype runs and for relatively small production runs.

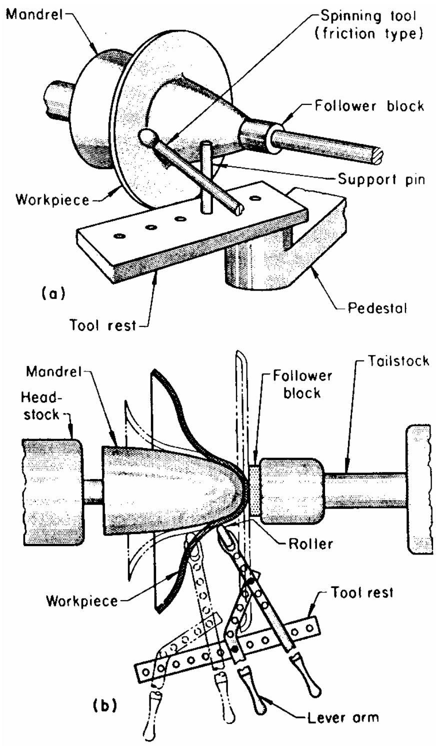


Figure II-5-1. Two examples of manual spinning using a lathe. (a)—A simple setup using a hand tool applied as a pry bar. (b)—A setup using scissor-like levers with a roller tool.[22]

Beryllium sheets up to 5.1 mm thick have been successfully formed by spinning.[10] Beryllium sheets that are less than about 1 mm thick are usually sandwiched between two 1.5-mm sheets of low-carbon steel. The sandwich is heated to 620 $^{O}$C prior to spinning. The steel sheets help to prevent buckling and maintain temperature. Sheets larger than 1 mm thick are usually not sandwiched and are heated to between 730 and 815 $^{O}$C. The workpiece and tool may be torch heated during spinning. Lubrication, which is especially important in spinning, is usually done with colloidal graphite or glass.[10] Hemispheres up to 79 cm diameter and 0.51 cm thick have been produced using glass lubricants.

## II-6. Three-Roll Roll Forming

Three-roll roll forming is a process for forming smoothly contoured parts, such as plates, bars, beams, etc., into various shapes by applying three-point–bending forces progressively along the surface with usually one or more of the rolls being driven. For beryllium, this usually involved the formation of curved panel sections and cylindrical shapes.[8] There are two basic types of three-roll-forming machines: the pinch-type and the pyramid–roll-type machines, which are shown in Figure II-6-1. Both types operate with two driven rolls and one bending roll, the latter determining the amount of bend (curvature) to be obtained. Two of the pinch types are shown in views (a) and (b). The ends of the formed part are shown as being flat in view (a). The flat ends, if present, must generally be removed. The pyramid type is shown in views (c) and (d), the difference between the two being only in that the ends were pre-bent in view (d).[23] With the pinch-type machine, the flat ends can be avoided or minimized by pre-forming the ends. This can be done by reversing the rotation of the rolls and feeding a short length from the rear. With the pyramid-type machine, the ends cannot be flattened by this technique; other flattening means, such as pre-flatting in a press brake, must be used. The use of combining the beryllium sheet with a sufficiently longer sheet (e. g., of stainless steel) to lead in and out the beryllium was used to eliminate flat ends.[8] The flat ends can be virtually avoided by incorporating a forming "shoe" at the entry of the pinch-type machine as shown in the figure. The shoe pinch-type machine lends itself to automation and is therefore used primarily as a production unit. However, it is limited to smaller thicknesses and widths and to round cylinders and is only applicable to cold forming.[23]

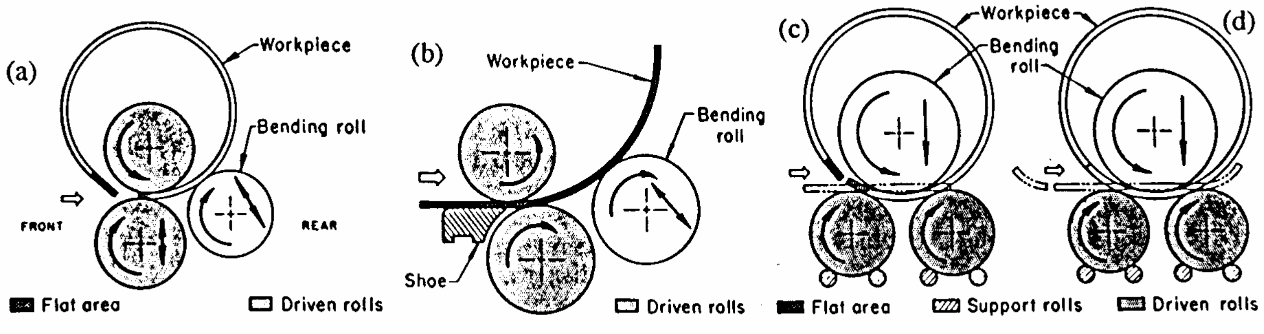


Figure II-6-1. End views of different setups for three-roll forming. (a)—Conventional pinch-type machine. Note large flat area on the leading end and smaller flat end on trailing end. (b)—Shoe-shape machine with two powered rolls. (c) and (d)—Arrangement of rolls in a pyramid-type machine. Note flat leading and trailing ends shown in (c) are minimized in (d) by prebending.[23]

The pinch-type machine produces a truer cylindrical shape than that which is obtained with a pyramid-type machine. This is because, of the two machines, the pinch-type machine allows the workpiece to be held more firmly against the rolls. In the pinch-type machine, the bending roll is rotated by the friction between it and the workpiece. It is adjusted angularly to produce a specified diameter. The roll is depicted in Figure II-6-1 (a) as being at an angle of 30 degrees. In the pyramid-type machine, the bending roll is adjusted vertically to produce a specified diameter. This type of adjustment offers the ability to attach (bolt) dies to the bending roll that permits forming of irregular shapes. Of the two machines, the pinch-type machine provides greater accuracy and for a given machine size it can produce a larger range of thicknesses.[23]

The minimum diameter that can be formed is determined by the diameter of the top roll for both machine types. Under optimum conditions, the smallest cylinder diameters that can be formed are: 50 mm larger than the top roll diameter for the pinch-type machine and 150 mm larger than the top roll diameter for the pyramid-type machine. Thin gage products may require support to prevent out-of-roundness. Maximum width and length dimensions are basically limited by roll sizes and available space. Machines having 12.5-m rolls have been built.[23] Heat treatments and intermediate anneals of beryllium would be comparable to those used for other forming operations.

The amount of strain obtainable in a curving process without failure should be at least equal to the uniform strain obtained in a tensile test made under comparable conditions of temperature and strain rate. Three conditions can exist during bending as illustrated in Figure II-6-2: plane bending, with the neutral axis in the center of the sheet thickness; stretching, where the neutral axis is inside the inner surface; and shrinking, where the neutral axis is outside the outer surface. For simple bending through relatively large radii, the strain, e, is approximately related to the radius, r, and thickness, t, by the following expression:[8]

$$e \cong t/2r,$$

and for stretching, the strain is given approximately by the expression:

$$e \cong t/r.$$

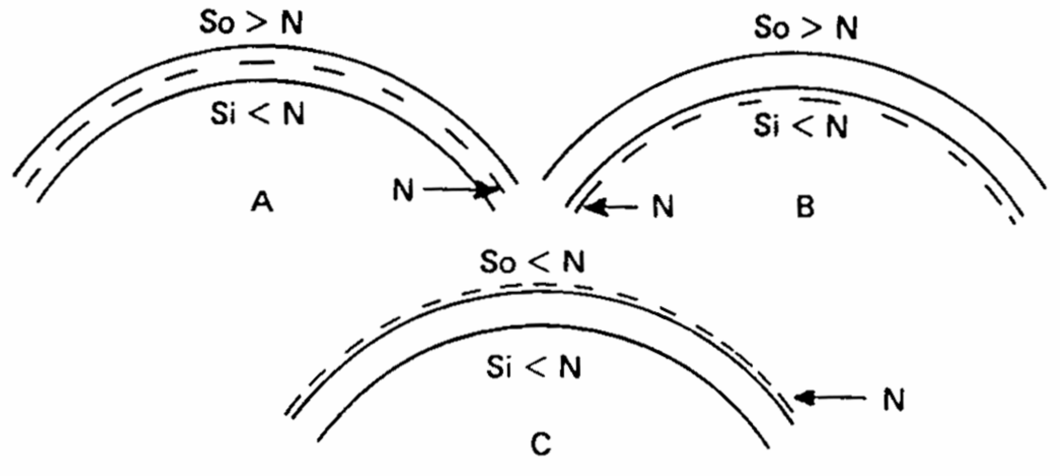


Figure II-6-2. Illustrations of the three conditions that can exist during bending. A— Plane bending, where the neutral axis, N, is near the center of the sheet. B—Stretching, where N is inside the interior surface. C—Shrinking, where N is outside the external surface.[23]

Two examples of precision three-rolled-formed cylinders were reported, both produced from ingot source beryllium.[8] A 50-mm-diameter cylinder was roll formed at room temperature from 0.5-mm-thick sheet in eleven passes. The cylinder, in which the ends of the formed sheet had been electron-beam fusion welded, was round to within ± 0.254 mm on the diameter. A 430-mm-diameter cylinder was roll formed at 700$^{O}$C from a 6.85-mm-thick by 305-mm-wide by 1.57-mm-long blank in five passes. The ends were joined using an electron-beam aluminum-shim weld and then machined to a uniform wall thickness of 5 mm and 475 ± 0.2 mm diameter.

## II-7. Stretch Forming

Stretch forming involves shaping a part (rolled or extruded sections) by applying tension while wrapping it over or around a block having the desired contour. The metal is stretched just sufficiently beyond its yield point to retain the stretched shape. When applied to beryllium the wrapping operation usually takes place quite slowly undergoing some creep. It is also referred to as creep forming.[8] Both open and closed-die tooling can be used, the former tooling being most commonly used for beryllium. It consists of a male die with the desired contour and the means of forcing the blank to assume that contour. In closed-die tooling, the male die is used to force the blank into the female blank, forcing it to assume the contour of the male die. Friction forces from the female die help to restrain the part and cause a stretching condition. In closed-die tooling, both dies can be heated, lending itself to heating the part and maintaining the desired temperature. Since the high modulus of beryllium will resist buckling or warping, tension may not be necessary.[8]

Examples of stretch forming, which are presented in the ASM Metals Handbook[24], are reproduced in Figure II-7-1. Four methods of stretch forming are illustrated:

- Stretch draw forming — views (a) and (b)
- Stretch wrapping, also known as rotary stretch forming—view(c)
- Compression forming—view(d)
- Radial draw forming—view(e)

View (b) can be considered as an example of closed-die stretching.

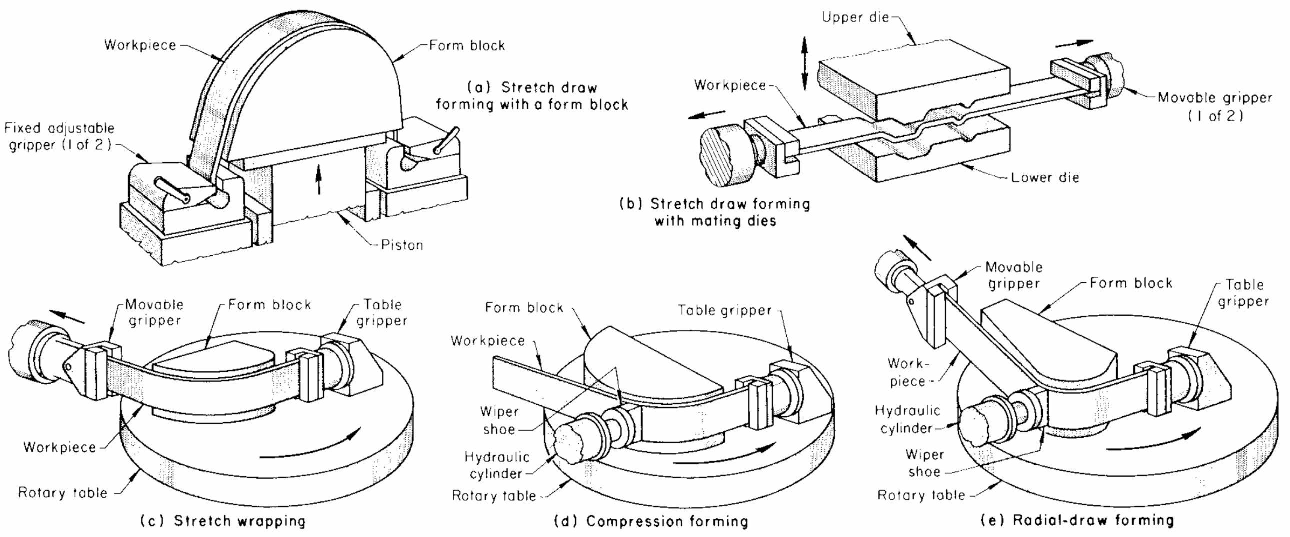


Figure II-7-1. Illustrations of techniques involved in the four basic methods of stretch forming: (a) and (b)—stretch-draw forming, (c)—stretch wrapping, (d)—compression forming, and (e) radial-draw forming.[24]

In general, excessive tension will induce cracking. Insufficient tension may result in poor contouring, wrinkling, or springback of the formed part. An estimation of force required for stretching a part is given by the following:

$$F = A(Y + U)/2,$$

where F = stretch-forming force, A = transverse cross-section area of part, Y = yield strength, and U = ultimate tensile strength. This would represent an average force. It does not take into account work hardening, friction, complex contours, etc. It is suggested that for certain complex parts an additional 25% may be added to the calculated value.[24] Surface finishes may be protected by using “carrier” sheets[h]. An alternative may be to use a polyvinyl-chloride coating instead of a lubricant and/or by careful cleaning to eliminate abrasive dust particles.

Several examples of stretch forming beryllium were reported. Beryllium panel blanks, measuring 627 x 716 x 1.4 mm and 570 x 358 x 1.4 mm, were stretch formed to a radius of curvature of 762 mm using either open-die or closed-die tooling. In the open-die tooling, a blank was heated to 732$^{O}$C using quartz lamps and creep-formed to the male contour with a weighted wire mesh. In closed die tooling, the dies were heated to 732$^{O}$C, and a flat blank that was preheated to the same temperature was placed between them; the dies were then closed within one to two seconds. To avoid warping during cooling, the curved panels were placed in a set of unheated dies, which resulted in the cooling being more uniform than when cooled in the original dies. In another example, a U-shaped longeron was formed in a closed die heated to 632 $^{O}$C. The flat blank was heated to 743 $^{O}$C and formed at a rate of 13 to 25 mm/min.

Some of the advantages offered by stretch forming that are listed in the ASM Metals Handbook are the following:[24]

- About 70% less force is needed than that required with conventional press forming.
- It can reduce material costs by as much as 15% compared to other forming methods.
- There is little likelihood of buckles and wrinkles since the stretching is done over the entire area of the workpiece.
- Springback is greatly reduced. Although there is some springback, it is easily controlled by over-forming.
- Residual stresses are low.
- Changeover is easy as tooling is simple.

Some limitations or disadvantages are the following:[24]

- It is limited in its ability to form sharp contours and reentrant angles. It is at its best in forming shallow or nearly flat contours.
- If the workpiece is not pinched between mating dies, there is no opportunity to coin out or iron out slight surface irregularities.
- In some of the methods, such as in stretch wrapping, the process is relatively slow and not suited to high-volume production. Stretch-draw forming with mating dies, however, can be done as rapidly and automatically as forming with conventional press operations.
- Deep forming in the direction of the free edges is not practical.
- Best for rectangular blanks.
- Metals with very nearly similar yield and tensile strengths may require automatic equipment to determine and control the amount of strain for uniform results (without the danger of fracturing).

## II-8. Wire Drawing

Drawing is the reduction of the cross section of a shape (rod, bar, tube, or wire) by pulling it through a die. A number of successive dies may be required to achieve the final dimension. It

---

[h] The blank (workpiece) is sandwiched between or covered by protective sheets, called carrier sheets, which are subsequently removed from the blank after stretching.

allows obtaining closely controlled dimensions in long products with constant cross sections. Excellent as-drawn-surface finishes are attainable. A number of drawing methods are illustrated in Figure II-8-1

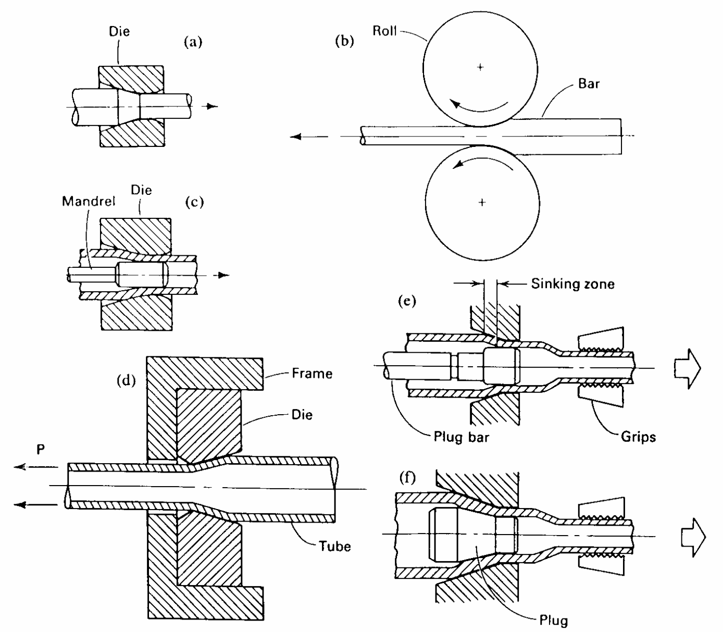


Figure II-8-1. Schematic examples of some drawing methods: (a)—wire drawing, (b)—bar drawing with undriven rolls, (c), (d), (e), and (f)—tube drawing. View (d) shows drawing without any mandrel, (e) with fixed plug, and (f) with floating plug if a fixed plug will stretch or break.[25]

Excessive draw-force can lead to unstable deformation. For practical reasons, the draw-force is usually limited to about 60% or less of the as-drawn flow stress, giving reductions of about 15 to 35%. Depending on the product, much larger single reductions could be attainable by extrusion.[25] For example, a reduction in cross section of 83% (100:17), which can be accomplished by one extrusion pass, would require five drawing passes on corresponding die sizes, assuming 30% reduction per pass. Wire drawing would be used for production of large quantities of small-diameter wire (e.g., 0.01mm dia.) requiring excellent dimensional control with good surface finish.

Beryllium wires have been produced to sizes down to 0.125 mm diameter in 3000-m-continuous lengths using standard equipment. Smaller lengths of 0.025-mm-diameter filaments have also been produced. Beryllium undergoes extensive deformation when drawn without intermediate anneals from 9.5 to 0.125 mm diameter.[26] This corresponds to a reduction ratio in cross-section area of over 5776:1. Yield and ultimate tensile strengths as a function of the reduction of wire diameter wire are shown in Figure II-8-2. Starting with a diameter of 9.5 mm, the curves indicate that the strengths increase progressively with reduction until a diameter of about 0.70 mm is reached (reduction of 184:1), with the strengths remaining unchanged with further reduction.[26] In one study, maximum yield and ultimate tensile strengths of 1170 and 1570 MPa. respectively, with an elongation of 2.1% were obtained by drawing electrorefined-origin block. Heat treatment will generally increase ductility with a concurrent reduction in strength. Results from different time-temperature treatments are seen in Table II-8-1.[26] The reversals in elongation seen with increasing time or temperature at the higher temperatures were undoubtedly due to recrystallization and/or grain growth since recrystallization of the heavily worked wire was observed to occur at temperatures as low as 595$^{O}$C. Substructures as small as 0.1 µm were reported. Pronounced basal and prism textures parallel to the wire axis and randomly oriented with respect to the radial direction were reported.[26]

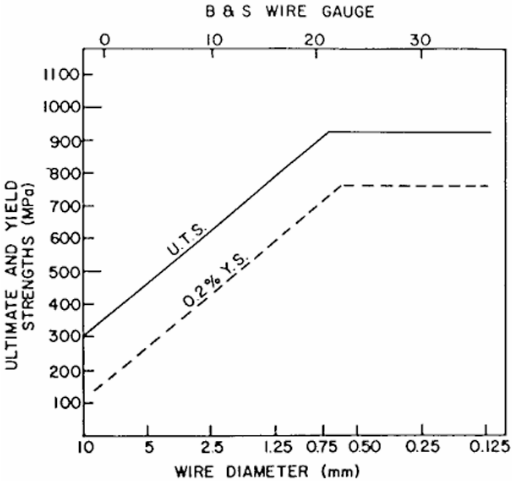


Figure II-8-2. Yield and ultimate-tensile strengths of beryllium wires as a function of reduced wire diameter after successive reductions without any intermediate anneals.[26]

Because of its enhanced purity level and cleanliness providing greater drawing reliability, electrolytic flake was the preferred beryllium source. The high purity resulted in a drop in strength and an increase in ductility. Attempts were made, unsuccessfully, to increase strength by additions of BeO. Additions of a large number of intermetallic compounds as dispersions were also investigated. These insoluble dispersions (oxides and intermetallics) became segregated into striations running parallel to the drawing direction, causing a concurrent decrease in drawability.[26]

**Table II-8-1. Effect of Heat Treatment on Mechanical Properties of Beryllium Wire Drawn to 0.125 mm Diameter.**[26]

| Condition | Ultimate tensile strength, MPa | 0.2% yield strength, MPa | Elongation, % (in 25 cm) |
|---|---|---|---|
| As-drawn | 1198 | 941 | 6.3 |
| Heated to 425$^{O}$C 24 h | 1088 | 1040 | 0.8 |
| Heated to 540$^{O}$C 24 h | 924 | 836 | 5.0 |
| Heated to 595$^{O}$C 0.5 h | 972 | 765 | 11.0 |
| Heated to 650$^{O}$C 0.5 h | 793 | 538 | 13.9 |
| Heated to 655$^{O}$C 3 h | 780 | 469 | 17.3 |
| Heated to 655$^{O}$C 7.5 h | 697 | 427 | 11.1 |
| Heated to 705$^{O}$C 0.5 h | 752 | 427 | 11.7 |
| Heated to 760$^{O}$C 0.5 h | 629 | 345 | 9.0 |
| Heated to 815$^{O}$C 0.5 h | 468 | 276 | 6.5 |

Commercial practice of producing beryllium wire as reported in 1979 is presented in the following.[26] Cylinders, from ingot and hot-pressed block, measuring 9.5 cm diameter by 20 cm long, are encapsulated in steel jackets and hot extruded (950 to 1065$^{O}$C). The steels cans are removed by pickling in nitric acid. The extruded rods are then straightened and etched in an HF-

$HNO_3$ solution to yield drawing rods measuring 9.5-mm in diameter. The rods are drawn into wire or filament by warm drawing (400 to 425$^{O}$C), using drawing speeds up to 60 m/min. Die jaws are insulated and steps are taken to ensure heat retention during all stages of processing. Tungsten carbide dies with an included angle of 12.5 degrees are usually used for diameters greater than 0.5 mm while diamond dies are used at smaller diameters. Molybdenum-disulfide or fine-graphite-powder lubricants are employed during drawing. A 12.5% reduction per pass is typical, although reductions up to 25% are feasible. Use of a nickel jacket is often preferred over bare drawing in order to prevent galling and seizing. The jacket is placed on the beryllium during the initial drawing pass by co-drawing. It is removed by pickling in concentrated nitric acid. Three types of equipment are used depending on wire-size ranges: reductions from 9.5 to 1.85 mm are done on a mechanical draw bench, from 1.85 to 0.50 mm on a capstan-type drawing machine, and below 0.5 mm on multiple-pass drawing machines. In all cases the drawing assemblies are heated to 400 to 450$^{O}$C.

Internal-type defects having a chevron-like appearance may be produced when improper drawing procedures are used with beryllium as well as with other metals. These defects were often associated with low reductions in area and certain die configurations, whereby tensile stresses are generated along the centerline during or immediately after deformation. Temperature fluctuations below the desired drawing-temperature range may also cause centerline defects.[26]

Ingot-origin wire has a rough surface after jacket removal. This results from the relatively coarse grains inherited from the cast structure. The surface can be improved by chemical milling or by chemical polishing. A preferred polishing solution contains 450 ml phosphoric acid, 25 ml sulfuric acid, and 52 g of chromic anhydride. Immersion of the beryllium wire in this solution for 15 seconds at 120$^{O}$C results in the removal of 0.0125 mm from the wire diameter with greatly improved surface smoothness. Wire is normally used in the as-drawn condition; it is not chemically polished or milled for most applications.[26]

## III. Net-Shape Processing

Net-shape processing of beryllium was first introduced to reduce the high cost of machining and the high production of scrap in fabricating a complex or intricate geometry. Usually about 65%, and as much as 90%, of the consolidated material ended in scrap and chips when starting with a typical solid, cylindrical billet.[27] Net-shape or, more commonly, near-net-shape (NNS) products can be produced either by direct hot-isostatic pressing (HIP'ing) or by cold-isostatic pressing (CIP) followed by sintering to close porosity. Any residual porosity can subsequently be removed by HIP'ing (CIP/sinter/HIP) or by warm forming in a closed die (CIP/sinter/warm form). Both of these operations may also provide for some dimensional adjustment of the part. The viability of producing NNS products was first demonstrated in1960 when a demonstration part was produced by HIP'ing.[27] The first major NNS product was an aircraft-brake component formed by CIP/Sinter/Coining[i], while the first NNS commercial product produced by HIP'ing was a mass-mounted-sight-sensor support structure.[2, 3]

Vacuum hot pressing uses uniaxial pressures ranging up to 8.3 MPa at temperatures between 1000 and 1200$^{O}$C to produce billets up to 183 cm diameter.[28] A HIP system installed at Brush Wellman in 1985 was capable of processing beryllium at temperatures up to 1250 $^{O}$C with

---

[i] Coining striking or sizing refers to an operation to sharpen or modify a radius or profile. Coining also refers to a closed-die squeezing operation in which all surfaces of a workpiece are confined or restrained, resulting in a well-defined imprint of the die on the workpiece. It can be done warm or cold.

isostatic (argon) pressures up to 103 MPa.[26] The mechanical properties of the HIP'd beryllium were found to be equivalent or superior to the VHP billet in all respects. A comparison of tensile properties between VHP and HIP consolidations is shown in Table III-1.[28]

**Table III-1.Comparison of Beryllium Specification of Mechanical Properties for VHP and HIP.[28]**

| Property | Beryllium Grade | | | | | |
|---|---|---|---|---|---|---|
| | S-200 | | I-70 | | I-220 | |
| | HIP | VHP | HIP | VHP | HIP | VHP |
| 0.2% Yield, MPa | 296 | 241 | 207 | 172 | 345 | 276 |
| UTS, MPa | 414 | 323 | 345 | 241 | 448 | 379 |
| Elongation,% | 3 | 2 | 2 | 2 | 2 | 2 |

For NNS products, it is preferable to use atomized spherical powders since these powders have much better flow characteristics than those that are obtained with the mechanical-attrited powders. This results in improved fill characteristics (especially for complex parts) and increased overall packing densities (62 to 65% compared to 50 to 55%).

Many examples of NNS products are presented in the literature.[1, 4, 29, 30] The most straightforward method of producing a NNS product is the direct HIP'ing process whereby the powder is loaded into a shaped can. The can is degassed in vacuum at about 600 to 700$^{O}$C to remove air and gases that had been adsorbed on the powder surfaces, then hermetically sealed, and finally HIP'ed. The final billet shape is dependent on the shape of the can. Shaped mandrels can be used to provide cavities in the billet. Cans are usually made of mild steel because they can be cheaply and easily fabricated (formed and welded) and easily removed from the shaped billet by etching or machining.[5] Mandrels are generally made out of copper, although too high a consolidation temperature[j] may limit its use. The copper can be removed by machining, by a nitric-acid etch, or by a combination of both. Dilute concentrations of the acid will not attack beryllium. A critical part of the procedure is the degassing step to remove entrapped air and gases adsorbed on particle surfaces and the subsequent hermetically sealing of the can. Residual gases may result in some distortion of the can during heating. Of major concern, however, is the presence of any residual moisture. At the elevated temperatures the water vapor will react with beryllium to form beryllium oxide and hydrogen. The increase in the oxide content may not pose a serious problem. The hydrogen (gas), being virtually insoluble in beryllium, will expand during any subsequent heat treatment of the HIP'ed product and may significantly increase porosity as well as cause distortion of the product.[1]

The effect of HIP temperature on mechanical properties for HIP'ed beryllium using three different types of powders is depicted in Figure III-1. The curves show slow continual increases in tensile strength up to 1050$^{O}$C followed by a rapid falloff while the elongations continue to increase within the same temperature range. The decrease in strength at the highest temperatures could be attributed to the increase in grain size. In a separate study, the results of HIP'ing an impact-ground beryllium powder at 744 and 1000 $^{O}$C are compared. No difference in the ultimate tensile strength was shown, while the yield strength was lower and the elongation was greater at the higher temperature.[1]Since HIP'ing is performed at much higher pressures than the pressures

---

[j] Copper and beryllium have a low temperature-congruent melting point of approximately 860$^{O}$C at about 5 wt.% beryllium.

used for VHP'ing, lower temperatures and shorter times can be used with HIP'ing to produce the same densities as those achieved with VHP'ing. Accordingly, finer grain sizes with improved mechanical properties are obtained with HIP'ed products compared to VHP'ed products.

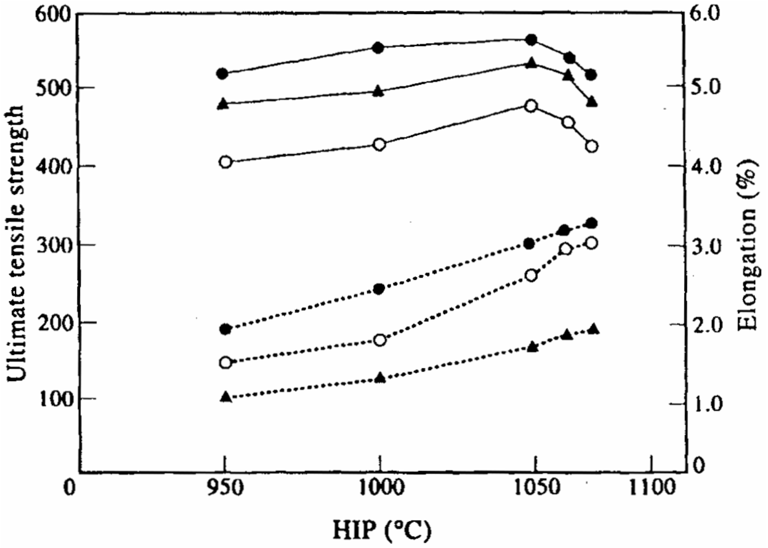


Figure III-1. Effect of HIP temperature on the ultimate tensile strength and elongation of three types of consolidated beryllium powders. Dotted line—elongation; solid line—ultimate tensile strength; ●—impact-ground powder; σ—ball-milled powder. o—disk-attritioned powder[31].

Instead of a shaped-can container, an inexpensive reusable elastic (e.g. neoprene or rubber) bag can be used to create an NNS preform by cold isostatic pressing (CIP). Pressure can be achieved by means of liquid. This yields a "green" body with a density between about 65 and 80% theoretical density.[5, 28] The effect of compacting pressure on the green density of beryllium is shown in Figure III-2.[28] Subsequent sintering can increase the density to up to 98% theoretical density. Greater densities may be achieved by HIP'ing (CIP/sinter/HIP) the sintered product.

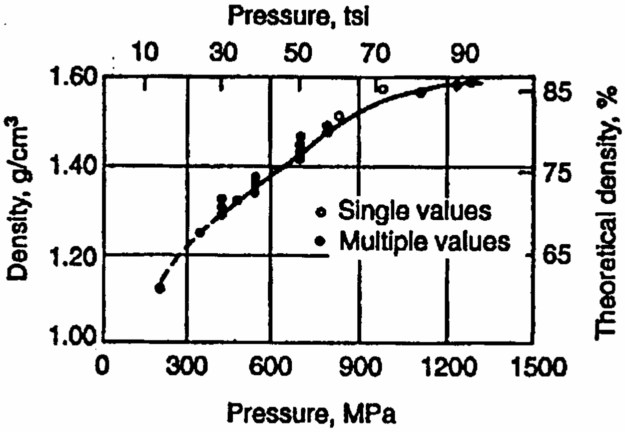


Figure III-2. The effect of compacting pressure on the green density of uniaxially cold-pressed-beryllium powder.[28]

**Table III-2. Properties of S-200F Consolidated by NNS Processes.[30]**

| Property | VHP | Direct HIP | CIP/HIP | CIP/Sinter | *CIP/Sinter/HIP* |
|---|---|---|---|---|---|

| | | | | | |
|---|---|---|---|---|---|
| Density, g/cc<br>(% theoretical) | 1.85 | 1.87<br>(100) | 1.86<br>(99.5) | 1.85<br>(99.3) | 1.86<br>(99.5) |
| Grain size, µm | 8.8 | 6.6 | 4.5 | 12.4 | 9.9 |
| 0.2% YS, MPa<br>Longitudinal<br>Transverse | <br>272<br>272 | <br>281<br>283 | <br>334<br>323 | <br>191<br>190 | <br>220<br>211 |
| Yield point, MPa<br>Longitudinal<br>Transverse | <br>283<br>278 | <br>283<br>290 | <br>336<br>330 | <br>---<br>--- | <br>---<br>--- |
| UTS MPa<br>Longitudinal<br>Transverse | <br>362<br>392 | <br>378<br>385 | <br>444<br>435 | <br>289<br>301 | <br>336<br>336 |
| Elongation, %<br>Longitudinal<br>Transverse | <br>3.0<br>5.7 | <br>3.2<br>4.2 | <br>3.9<br>3.8 | <br>3.6<br>3.8 | <br>3.6<br>4.4 |
| Microyield, MPa<br>Longitudinal<br>Transverse | <br>---<br>--- | <br>39.1<br>42.7 | <br>36.2<br>41.7 | <br>14.5<br>13.1 | <br>15.8<br>13.1 |

Experimental properties of S-200F consolidated by different NNS processes, which were obtained in an early investigation on NNS, are listed in Table III-2.[30] Direct HIP'ing was performed at 1000°C under a pressure of 103 MPa for three hours. The CIP'ing was performed using a cylindrical rubber bag, which was contained in a perforated aluminum cage to maintain the initial shape. Compacting was done at 276 MPa. The CIP'ed preform was then placed in a steel HIP'ing can and embedded in a granular refractory, which served as a pressure-transmitting medium. The can was then degassed, sealed, and HIP'ed as previously described. The CIP/Sinter product was CIP'ed as described above and then sintered at 1230 °C for 5 hours in vacuum. Each of the steps for the CIP/Sinter/HIP product followed the previously described procedures, respectively. The Hall-Petch relationship between strength and grain size that was obtained is shown in Figure III-3.[30]

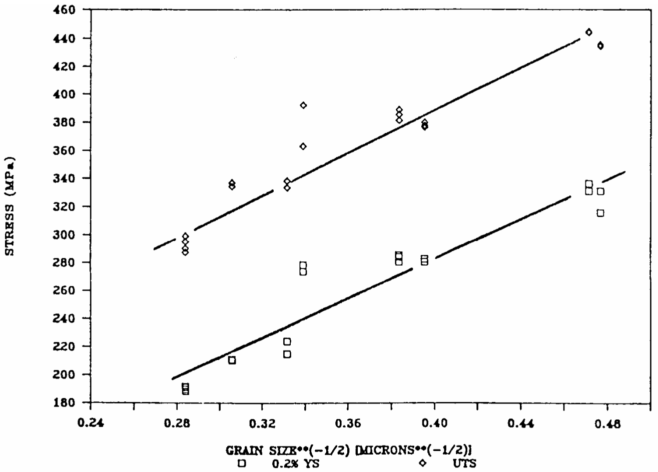


Figure III-3. The Hall-Petch relationship showing the effect of grain size on tensile yield and ultimate strengths of vacuum-hot-pressed, structural-grade S-200F beryllium.[30]

The HIP'ing can be done without the use of a can providing the sintered body has attained a density of about 96% theoretical density. In such cases, the HIP'ing is done at temperatures below those used for HIP'ing alone. The relatively high temperatures used in sintering, however, may have caused sufficient grain growth to lower the strength level below that of a VHP product using the same powder.[27] If applicable, a final step of warm sizing such as by coining or by some other deformation process may be applied. For example, a closed-die forging may be used to improve flatness of a mirror component; this would be followed by a stress relief treatment.[32] An alternative processing method may be to use a die press, instead of CIP'ing or HIP'ing, as indicated in the following sequence: die press/sinter/coin, whereby warm coining is used to achieve dimensional and density requirements. This has been used for the production of aircraft brakes, where the beryllium, with its high heat capacity and high melting point, also acts as an excellent heat sink.[1] Examples of manufacturing-cost savings obtained by HIP'ing parts produced by direct HIP'ing and by VHP'ing are shown in Table III-3.[1] The cost savings refer to all processing operations as well as material savings. Additional savings may arise by introducing additional procedures such as CIP'ing and sintering by eliminating the cost of can fabrication and can outgassing.

**Table III-3 Cost Savings on Comparing Direct HIP'ing with Vacuum Hot Pressing.**[27]

| **Shape**[a] | **Vacuum Hot Pressing** | | **Direct HIP'ing** | | **Cost Saving By HIP'ing** |
|---|---|---|---|---|---|
| | Input, Kg | Blank, Kg | Input, Kg | Blank, Kg | |
| "A" | 83.2 | 30.9 | 40.5 | 21.8 | 42% |
| "B" | 30.5 | 12.7 | 13.6 | 11.4 | 31% |
| "C" | 16.8 | 7.3 | 7.7 | 5.0 | 27% |
| "D" | 8.0 | 2.3 | 3.6 | 2.3 | 18% |

[a] Specific shapes were not presented.

In producing an NNS part, the can dimensions must provide for shrinkage that occurs during consolidation of the powder. The following expression was used to provide these dimensions for a preform that would be machined into a mast-mounted-sight structure (MMSS) having final linear dimensions of 235 x 248 x 305 mm:[33]

$$C = P/(D_c \times D_p)^{1/3},$$

where C = HIP can dimension, P = fully dense preform dimension, $D_p$ = preform density, and $D_c$ = tapped density[k] in the HIP can. The expression relates the linear shrinkage, given by $(D_c \times D_p)^{1/3}$, to the change in densities. Previous evaluations made with other pre-forms indicated that the shrinkage was isostatic (in the three orthogonal directions) with an average of 14% linear shrinkage. Slight shrinkage differences were due to corresponding density variations in the tapped density. To accommodate such differences, the HIP-can dimensions were based on having an excess shell of material around the preform for the MMSS. In addition to minimize the amount of required machining, the can was also designed to minimize welds and optimize component fit-up of the final structure. The powder-loading system was designed to provide a constant and continuous feed rate to the can as this leads to better density uniformity of the powder. The system was also designed to avoid any health and safety problems. The cans were sealed, evacuated, leak-tested, and then heated in an oven while being degassed to remove any gases and water vapor trapped on the powder surfaces. The degassing took a number of days before reaching a prescribed pressure ($< 10^{-4}$ torr).[33] The degassing stems were sealed off and the can was then HIP'ed in a hot isostatic press using argon gas at a pressure of 103 MPa at a temperature of $1000^{O}C$. The preform was then etched in a 40% (by wt.) nitric acid solution to

---

[k] The tapped density is the density of the powder prior to applying the consolidation pressure. The density of the powder is increased by a tapping (vibration) action during charging of the powder into the consolidation chamber.

remove the steel can. Finally, the preform was stress relieved at 800$^{O}$C for four hours and cooled at 50 $^{O}$C/hour to room temperature. Final machining included producing 2.03-mm-thick webs, reducing the 20.5-kg preform to a 2.73-kg part. A reduction of 50% in material costs was achieved with a part having better mechanical properties and a finer grain size than those developed by starting with the traditional VHP billet.[33] The same densities (1.85 g/cc) were obtained.

The low density (1.85 g/cm$^3$), high elastic modulus (303 GPa), high thermal conductivity (210 W/m·K), and moderate coefficient of thermal expansion (11.3 x 10-6/$^{O}$C) of beryllium make it the logical choice for optical components that require high precision and high stability. The high cost of beryllium, however, had prevented it from competing with other materials used for optics such as metal-matrix composites and silicon-nitride ceramics. With the development of NNS processing of beryllium using CIP/sinter/HIP or CIP/sinter/warm form technology, beryllium became competitive with other materials used for optics and is now widely used in optical applications. Furthermore, the NNS processing provides better dimensional control, improved isotropy of thermal and mechanical properties, and improved thermal stability compared to these characteristics obtained with traditional VHP beryllium.[29] In addition, in an all-beryllium optical system, the design is simplified since compensation for differences in thermal expansion where different materials are used does not enter, and sharper, more accurate images are attainable.[32] A number of examples of optical systems were reported.[29, 32]

In a CIP-HIP study of NNS processing for enhanced optical properties, beryllium powder was vibration fed into a rubber or plastic bag and CIP'ed at 260 MPa, achieving densities of up to 73% theoretical density. The green CIP'd blanks were degassed at 650 $^{O}$C for 26 hours, followed by four hours at 750 $^{O}$C.[30] The authors state that the HIP'ing pressure is typically 105 MPa with temperatures within the range of 760 to 1100 $^{O}$C. A secondary pressure-transmitting medium can be used to fill in the space between blank and can. Media that have been successfully used are sodium chloride, aluminum oxide, boron nitride, graphite, and glass balls. In using any of these media, it is important to consider the deformation compatibility between the medium and the blank during the HIP'ing cycle.[31] Homogeneous parts are obtained suitable for optical applications. The authors describe the properties for three different mirror configurations as examples of NNS products formed either by direct HIP'ing or by CIP/sinter/form and describe the fabrication of a light-weight-mirror structure in some detail.

One structure had a 25-cm diameter, closed-back mirror that consisted of flat front and back plates separated by honeycomb-shaped webs as shown in the cutaway view of Figure III-4.[29] The structure was made by HIP'ing the beryllium powder, which surrounded copper tooling and was contained in a fabricated steel can. The steel can is degassed and HIP'ed for three hours at 103 MPa. Holes in the back plate, centered above each cell, facilitated removal of the copper by nitric-acid etching. Copper was selected because of the following: good machinability, compatibility with beryllium under HIP'ing conditions, has higher CTE than that of beryllium and thus will not place the beryllium under tension on cooling from the HIP'ing temperature, and unlike beryllium, it is soluble in dilute nitric acid. During final machining, the part underwent a stress-relief procedure. As with all NNS processing of powders, shrinkages had to be evaluated. The diametrical and longitudinal shrinkages were 5.6 and 17.1%, respectively. The HIP'ed mirror-structure was observed to be distortion–free and the copper tooling did not suffer any deformation.[28] It was noted that in direct HIP'ing, the cost of the copper tooling (mandrels) and its removal was significant. In fabricating solid, plated-beryllium mirrors, total costs were reduced by using CIP/sinter/form instead of direct HIP'ing. The processing costs using CIP/sinter/form was slightly more for the processing but was only one third the cost for the beryllium compared to these costs for HIP'ing.[28] Structures as large as 1.2 m with web thickness as thin as 1mm can be produced by NNS processes.[6]

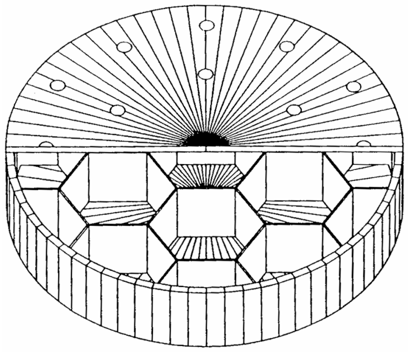


Figure III-4. Cutaway view of a light-weighted, closed-back, solid-beryllium mirror revealing a honeycomb-core structure made by using copper mandrels. Holes in the back plate, which were centered above each cell, facilitated removal of the tooling by nitric-acid etching after the HIP'ing operation.[28]

Inert-gas-atomized powders are the preferred powders for producing near-net-shaped beryllium products. The improved packing characteristics of the spherical particles, as compared to those produced by mechanical methods, provides for better control of the charge weight on filling the HIP cans. The improved packing enables achieving higher densities as well as better size control of the HIP'ed product.[32]

## IV. Rapid Net-Shape Forming

The term "rapid-net-shape forming" (RNSF) applies to a net-shape process that provides the means to manufacture intricate and complex components, including those designed with internal passages and very thin walls.[34] Parts with hollow passages or cavities will contain cores with corresponding geometries. The process is initiated with the design of a sacrificial wax pattern based on the part geometry and adjusted to accommodate shrinkage and shape change that would occur during consolidation of the powder. The pattern is then fabricated using rapid prototyping (RP) technology. This involves developing the model using 3-D computer-aided design (CAD), converting the CAD data into a stereo-lithography (STL) file, which is used to slice the CAD model into hundreds or thousands of cross-section layers. The part (in this case a mold) is then formed, using a stereo-lithography apparatus, by depositing a liquid polymer (droplets), layer by layer, onto a rising platform contained in a tank. A laser-generated beam, which traces out the cross sections and solidifies the polymer, controls the deposition and geometry of each layer and the rising platform. Epoxy is the mold material. The speed and low cost of the process allows for many modifications of a design.

The epoxy mold serves as a wax-injection die to produce a wax pattern with close tolerances. Ultra pure nickel is then evenly deposited over the wax pattern by electroforming. The wax pattern is removed from the nickel electroform by investment-casting techniques and the nickel is cleaned. A seamless nickel canister, which precisely replicates the shape and surface texture of the pattern, is thus obtained for hot-isostatic pressing a part. Sulfur and other contaminants from the electroforming bath must be kept at a minimum. The contaminants, especially sulfur, can impair ductility of the nickel as a result of grain-boundary precipitation during HIP'ing. Similar loading, evacuation and pressing procedures as employed in conventional HIP'ing are used. Free-flowing spherical powder is used to provide the maximum packing density and fill uniformity, both reducing the tendency for distortion during HIP'ing. A ceramic exoskeleton designed to prevent distortion while allowing the gas to pressurize the canister walls and the canister being seamless further reduce the tendency for distortion.[2] The use of an exoskeleton would depend on the contour complexity of the part. HIP'ing cycles must be compatible with the capabilities of the canister. Beryllium may be HIP'ed at 1010$^{O}$C.[34] The nickel, as well as any cores, which may have been added for passages and cavities, are dissolved in nitric acid. Parts ranging from a few centimeters to as large as a 60-cm cube have been made.[34] Several examples of rapid-net-shaped-formed parts were reported.[2, 34]

## V. Machining Overview

Beryllium is readily machinable. Excellent surface finishes and close tolerances can be obtained with the fine-grained beryllium produced from powders. By contrast, due to its coarse-grained microstructure, machined surfaces of cast beryllium, however, are frequently rough. Although beryllium is relatively soft (Rockwell B 80 to B90, depending mainly on its oxide content), it is abrasive, producing a discontinuous chip.[35] This characteristic causes tool-edge erosion when improper design or a wrong material is selected for the cutting-tool edge. The chips tend to become more continuous with decreasing oxide content. The abrasiveness of beryllium will rapidly wear down tooling, degrading accuracy and may cause excessive scrap due to repeat machining of machined parts requiring tight tolerances. The abrasiveness (tool wear) decreases with decreasing oxide content. The oxide content appears to have a greater influence on tool wear than does the work hardening factor of the beryllium. Tungsten-carbide tooling will provide two to three times the cutting life of high-speed tools.[36] It is suggested that both the tool-wear resistance and surface finish may be enhanced by honing or lapping the tool-cutting surfaces. The use of a sharp tool is important in reducing the tendency or extent of machining surface damage, which is a common occurrence with beryllium. A grade 2, general-purpose carbide cutting tool used for cast iron and non-ferrous materials is recommended with preference of specific grades within this class such as Valenite VC-2, or equivalent.[9, 35] Excellent results are attainable with this grade for medium to light cuts on long workpieces with extensive cutting-edge coverage. With few exceptions, beryllium has similar machining characteristics to those of chilled (hard) grey cast iron and to heat-treated-aluminum castings and, accordingly, it uses similar machining practices.[35, 36] Beryllium has a machinability factor of 55% using Grade 1112 free-machining mild steel as 100%.

The machining blanks, which are typically cut out from beryllium blocks, are usually in a high state of residual stress, which at times may be quite complex. These residual stresses may cause severe machining problems, especially if they continually vary during the machining. A stress-relieve treatment of up to two hours in the temperature range from 570 to 800$^{O}$C followed by controlled slow cooling is recommended. The cooling rate should not exceed 150$^{O}$C/hour. The recommended cooling rate for large sections can be as low as 20$^{O}$C/hour.[36]

Beryllium, being a brittle material, will easily chip or break if roughly handled or if inappropriately supported. Sharp corners should be avoided The metal has a tendency to chip or edge crack as the tool enters or leaves the part. To minimize this problem, chamfering of edges, especially corner edges, should be included in the design of the part. Cutting should proceed from the corner edges inward, finishing in the center of the part. Using run-off material as well as light cuts may also be helpful. When drilling or tapping through holes, backup support (brass or free-cutting mild-steel fixtures) should be used to minimize breakthrough damage. Any steel scrap can readily be separated magnetically from the beryllium scrap, while both brass and steel can be dissolved by nitric acid. To prevent possible distortion and /or cracking, soft jaw chucks that provide as large a contact area as possible should be used; excessive pressure should be avoided.[35-37] Machining on centers should be done using live (rotating) centers in contrast to dead (stationary) centers; in the latter case carbide centers with lubricants must be used.[37] Since beryllium has a relatively low precision elastic limit with the possibility of microcreep, care must be taken in cutting, handling, or storing unsupported thin regions as a permanent set may develop.

Because of the high value of beryllium scrap and the cost of decontamination, where practical, beryllium should be machined dry. Dry chips have a higher salvage value than wet chips. Accordingly, heavy stock removal is usually performed dry. Advantages of wet cutting are improved cutting action and a reduction of airborne beryllium dust. Health hazards may also dictate the use of wet machining/cutting. In some operations, wet cutting must be used due to the difficulty in collecting dry chips and/or to flush chips away from the cutting region such as in grooving and drilling. Coolants should also be used where excessive heat may be generated. For best results, beryllium should be finish-machined with coolants.[35] Care must be taken that the wet coolant or cutting oil does not react with the metal and that it does not dry out and allow dust to form. The coolant and/or cutting oil should be washed off in a solvent and the machined part should be dried. Distilled, deionized water should be used for mixing with water-soluble oils, which are the preferred oils (typically one part oil to 20 to 30 parts water). These oils should be changed about once a month and the pH level maintained according to specifications. Oils should be free of sulfur and free of free chlorine.

The beryllium should not be exposed to cutting oils or coolants for an extended period of time, lest the beryllium becomes etched or corrosion be initiated. For example, a galvanic couple can develop between the beryllium and the metal fixture when exposed to the coolant. Operations using brass-fixturing of beryllium in contact with water solubles should be limited to less than 30 minutes.[37] The galvanic action may be prevented by coating the fixture with a polymer such as PTFE, which is a pure Teflon (polytetrafluroethylene). Liquid Freon TF (trichlorotrifluoroethane) was shown to be a good coolant and lubricant. A coolant grade especially formulated for beryllium is Prochem Tripple C Type 5505.[35] After using coolants, neutralization of a part should be done before storage, assembly, or packaging. This can be accomplished by immersion in perchloroethane followed by air drying. Freon is recommended as the agent for ultrasonic cleaning. Contact with alcohol or halogens should be avoided.[36]

Government regulations limit the maximum in-plant atmospheric concentration of beryllium to 2 $\mu g/m^3$ (probably, this will soon be changed to 0.2 $\mu g/m^3$) as an average concentration for an 8-hour day.[9, 38] Exposures to 25 $\mu g/m^3$ for up to 30 min. are allowed, but, concentrations over this amount is unallowable for any period of time. For machining operations, an appropriate hood and exhaust system should be installed, enclosing the workpiece, cutting tool, and chuck. Where a hood may not be practical, an exhaust nozzle alone can be used, which should be located no further than 13 mm from the cutting tool. Although the speeds and feeds of typical lathe operations are similar to those applicable to cast iron, they are often limited by the efficiency of the dust-extraction and chip-collection systems. The operation must be approved and monitored by an industrial hygienist. Polishing of the machined workpiece must be done in a glovebox or, if using a lathe, under a hood.[38] Hazards and protective measures associated with beryllium operations are discussed in a report (soon to be published by author) dealing with these subjects.

Machined-surface-damage problems and the different machining operations that are applicable to beryllium are discussed in the following sections. Computer-aided design/computer-aided manufacturing (CAD/CAM), which is increasingly more utilized in the design and manufacturing of components and systems, will not be discussed in this report. An excellent description of CAD/CAM for machining operations is presented in the ASM Handbook on Machining.[39]

## VI. Machining-Surface Damage

Beryllium is susceptible to surface damage during machining which, if not removed, will degrade its mechanical properties. The surface layer of a machined part typically will contain microcracks and a network of twins[1] (detected metallographically) that can lead to brittle fracture. The formation of twins is caused by the machining-induced stresses. The depth of the damage is largely dependent on the severity of the machining operation. Twins tend to propagate readily through a grain, but propagate with difficulty across a grain boundary, Therefore, the extent of damage is also related to the grain size. It appears that the depth of machining damage increases with increasing grain size and, accordingly, increasing grain sizes require increasing the depth of surface removal, which is done by chemical machining (based on etching). The depth of the twinned region typically may range from 0.05 to 0.5 mm, and it appears to be less with a decrease in the grain size.[40] For fine-grained material, deformation (mechanical) twins have been detected to depths of 250 µm below the machined surface. For a grain size of 25 µm, this depth would correspond to 10 grains. It is generally accepted that the damage depth for fine-grained beryllium under normal machining practice is about 10% of the depth of the cut.[36] The surface grains are much more heavily twinned than the subsurface grains, and the degree of twinning decreases with surface depth. This is illustrated in Figure VI-1, which shows a plot of the number of twins remaining on the etched surface as a function of etch depth for machined S-200 beryllium having a grain size ranging from 35 to 50 µm.[40] The analysis was made using both direct observation and acetate replicas of the surface examined at 400X. In this study it was noted that microcracks, laminations, and smeared metal were completely absent after an etch depth of 0.025 mm.

---

[1] Beryllium has a c/a lattice-parameter ratio that is less than ideal for an HCP crystal structure. Since a compressive stress perpendicular to the basal plane (parallel to the c-axis) will compress the c-axis to become still further from ideal, reorientation of parts of the grain (twinning) occurs to relieve this contraction (increased energy). Similarly, twinning will occur under a tensile stress parallel to the a-axis. The twinned regions, which have undergone a rotation of 84 degrees, become mirror images of the untwined regions across their interface within a grain. The presence of mechanical twins (in contrast to annealing twins) generally leads to a tendency towards crack nucleation and reduced ductility in HCP metals.

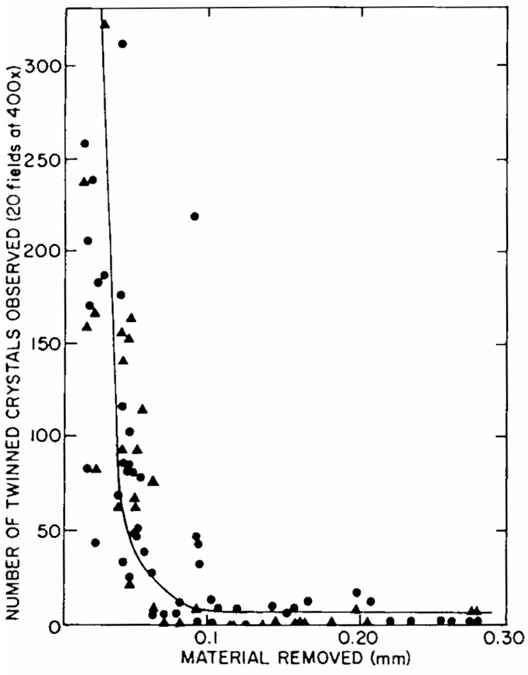


Figure VI-1. Number of twins observed on the etched surface of a machined beryllium as a function of depth of etching: σ—direct observation; ●—replica observation.[40]

Surface damage, if not removed, can result in a large drop in both fracture strength and elongation. Although the yield strength may not be significantly affected, elongation can be reduced to a fraction of the damage-free elongation.[35] Regardless of grain size, etching is recommended to remove approximately 100 μm from each machined surface.[35,41] This amount of removal, which assumes that the proper machining practices were used, generally results in a marked improvement in mechanical properties even though the calculated critical crack sizes for beryllium are larger than this value, namely, between 0.2 and 1 mm.[42] It was generally observed that for tensile-test specimens, etching 0.08 to 0.13 mm off from each surface was sufficient to remove nearly all the detrimental effects of most machining treatments even if etching to that depth range did not remove all the metallographically detectable damage.[40]

In fabricating the space-shuttle orbiter, it was determined that the removal of 0.152 mm (0.006 in,) of metal by etching was required to eliminate the presence of all machining-induced twinning; and, this was done without creating excessive dimensional tolerance problems (except for holes in thick sections).[43] The ASM Handbook states that typical machining damage ranges from 0.025 to 0.10 mm for most machining and may extend to a depth of 0.50 mm depending on the machining method.[38] Brush Wellman states that with good practice the damaged layer should generally not exceed a depth of 51 μm (0.002 in.); however, under severe machining, depths of 0.254 mm may be obtained. They also state that surface damage must be restricted to a maximum depth of 102 μm (0.004 in.) in machined structural surfaces. This depth of damage can be eliminated by either a stress relief or an acid etch. Excessive removal of damaged surface material by etching will decrease dimensional-tolerance control. Experience has indicated that very close tolerances can be maintained with surface removal of as much as 127μm.[35]

Etchants commonly used for chemical milling are 2%HF-2%$HNO_3$-2%$HSO_4$;[35, 44] sulfuric acid solutions; nitric/hydrofluoric acid solutions; and ammonia bifluoride,[44] with the latter three indicated as depending on the application. Other etchants used were given as 15% ammonium bifluoride; 20% nitric acid-1% hydrofluoric acid;[40] 10% distilled or deionized water-127 g dry chromic acid-75% phosphoric acid-15% sulfuric acid; and 25% nitric acid-0.25 to1.0% hydrofluoric acid-balance of distilled or deionized water.[45]

In the absence of microcracks and where the damage is due only to mechanical twinning, and where dimensional tolerance is important, a two-hour anneal at 800$^{O}$C may be sufficient to preserve the desired properties. This anneal is also adequate to remove any residual stresses and essentially restore the pre-machined, room-temperature mechanical properties.[41] Examination under polarized light at a magnification of 250X of polished cross-section surfaces of machined samples, which experienced the same thermal history as the machined parts, should indicate the condition of the heat-treated surface of these parts.[9] The use of heat treatment may not be feasible for temperature sensitive structures, for example, structures containing brazed joints.

In general, for tensile-load-bearing (or any critical components), etching and/or a stress-relief treatment is recommended following machining. Etching (chemical milling) can be used to remove the machining-damaged layer. This is accomplished by immersing the part in an acid solution for a specified length of time. The removal, however, can be uneven and cause a loss of precision tolerances. Heat treatment, which removes the mechanical twins, will not affect dimensional tolerances except for possible distortion. Annealing twins may form, but they will not affect the mechanical properties. Whereas heat treatment will not remove all of the surface defects (e. g. machining cracks), etching, in removing damaged metal, will also remove all the possible defects contained in the damage-removed metal. Nevertheless, in general, in the absence or even with a slight presence of machining cracks, annealing appears to be as effective as etching in restoring mechanical properties of machined parts. Most investigators concluded that machining cracks are less significant than mechanical twins in affecting mechanical properties.[40] Table VI-1 lists some mechanical properties of S-200E beryllium in the following conditions: before machining, as-machined, machined-and-annealed, and machined-and-etched condition.[38]

A stress-relief-anneal schedule proposed by Brush Wellman (BW) is as follows;[35]

- Select a high-vacuum furnace to minimize oxidation and discoloration.
- Heat part to 760$^{O}$C ± 5 $^{O}$C (In a more recent BW report 790 $^{O}$C is used[44]) and hold for one hour for each 25.4 mm (inch) of cross section.
- Vacuum cool from 760 to 690 $^{O}$C at a maximum rate of 5 $^{O}$C/hr. and from 690 to 200 $^{O}$C at a maximum rate of 50 $^{O}$C/hr. For very large sections the two rates should be limited to a maximum rate of 20$^{O}$C/hr. An inert-gas atmosphere may be used below 690 $^{O}$C.

**Table VI-1. Transverse Tensile Properties of As-Machined, Annealed, and Etched Grade S-200E Beryllium.**[38]

| Condition | | Ultimate tensile strength, MPa | 0.2% yield strength, MPa | Elongation, % |
|---|---|---|---|---|
| **Pre-machining** | | 366 | 227 | 3.7 |
| **As-machined** | | 263 | 216 | 0.7 |
| **Machined And Annealed at °C** | 400 | 218 | 193 | 0.5 |
| | 500 | 207 | 199 | 0.3 |
| | 600 | 282 | 187 | 2.0 |
| | 700 | 353 | 205 | 3.6 |
| | 800 | 343 | 230 | 3.1 |
| | 900 | 347 | 249 | 3.2 |
| | 1000 | 342 | 239 | 3.3 |
| **Machined and Etched** | 25 µm | 323 | 209 | 2.8 |
| | 50 µm | 337 | 220 | 2.8 |
| | 75 µm | 333 | 216 | 3.1 |

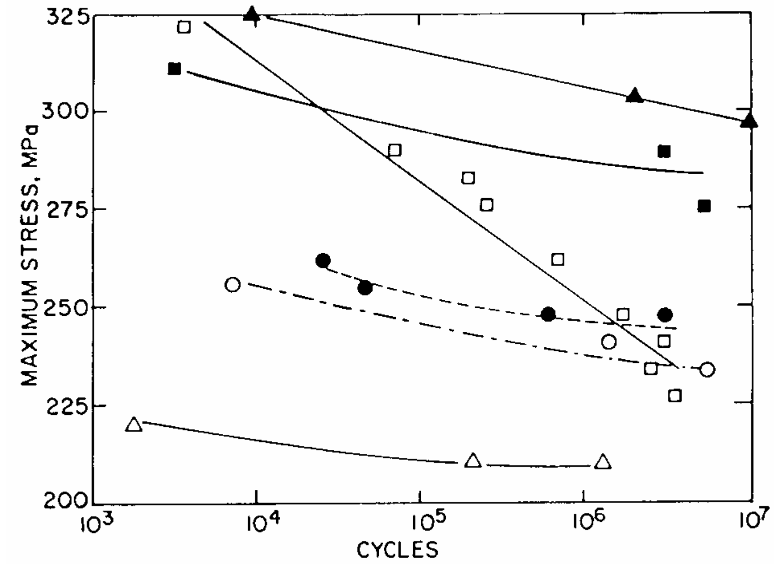
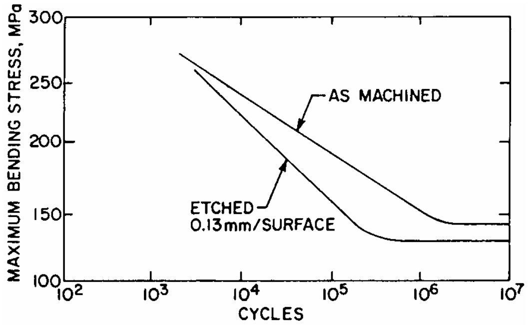


Figure VI-2. Effect of various treatments on the fatigue life of extruded ingot beryllium:σ—annealed, etched 0.46 mm deep; ■—annealed, etched 0.46 mm deep (245 MPa); ●—annealed, etched 0.05mm deep (236 MPa); □—annealed (259 MPa); ○—as-machined, etched0.05 mm deep (275 to 400MPa); △—(210 MPa). Numbers in parentheses refer to UTS.[40]

Fatigue properties were shown to be significantly improved after removing the machining-damaged surface by etching and/or annealing as indicated in Figure VI-2 for extruded ingot beryllium. An unusual contradiction to these results is shown in Figure VI-3 where the fatigue behaviors of machined and of machined-and-etched ingot-sheet material are shown. This unexpected result was attributed to the possibility that the residual surface compressive stresses outweighed the detrimental effects of the surface twins in the as-machined specimens.[40]



FigureVI-3 Effect of etching on the fatigue behavior of machined ingot-sheet beryllium.[40] Note that the results are opposite to what would be expected. This was attributed to residual compressive machining stresses dominating over the removal of surface damage.

Figure VI-4 shows that the impact-toughness-transition temperature of ground Charpy unnotched specimens of beryllium was lowered by etching to a depth of 0.05 mm. Significant improvement by etching was obtained in the ambient-temperature region. These and other results show that the two sets of toughness values tend to converge at elevated temperatures. It was also observed that the detrimental effects of a basal orientation that results in basal-plane fracture may actually become more significant than surface damage in affecting impact toughness of beryllium.[40] Note the low toughness values shown in Figure VI-4 for the shot-peened specimens independent of temperature.

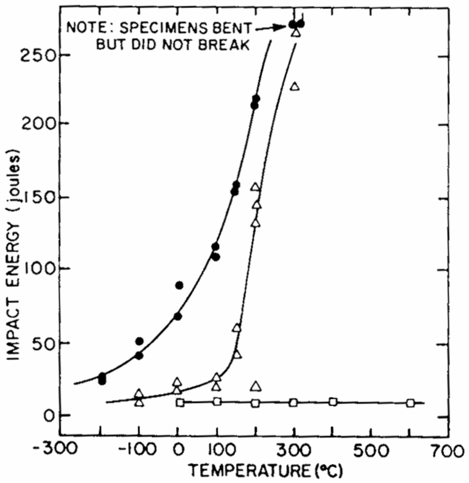


Figure VI-4. Impact behavior of unnotched Charpy specimens obtained from hot-upset-beryllium sheet: △—as ground;●—ground and etched to 0.05 mm depth;□—shot peened.[40]

Some studies have been reported on evaluating the effect of machining temperature on surface damage. Lathe turning of hot-pressed S-200, fine-grained (10 μm dia.) beryllium at 400$^{O}$C, which is above its ductile-to-brittle-transition-temperature (DBTT) range, essentially eliminated the development of twinning, microcracks and residual stresses. Figure VI-5 shows the effect of cut depth on depth of twinning for the same material at several temperatures below 400$^{O}$C, namely, ambient, 230, 290, and 340 $^{O}$C. A decrease in machining temperature resulted in a deeper penetration of twinning for a given cut depth, although the differences between the three higher temperatures are minor. At ambient temperature, the ratio of twin depth to cut depth is about 0.05; at the higher temperatures it is about 0.004. Residual stress after machining at ambient and at 400°C were also compared, giving residual compressive stresses of 55 and 3 MPa, respectively, above the residual stresses present in unmachined material. Differences obtained between machining at 400°C and at the lower temperatures were attributed to the additional slip systems operating at the higher temperature, i. e., above the DBTT. In contrast to these results, one study reported that no significant difference in twin depth was found (metallographically) by lathe turning at temperatures of-70, 25, and 250 °C.[38]

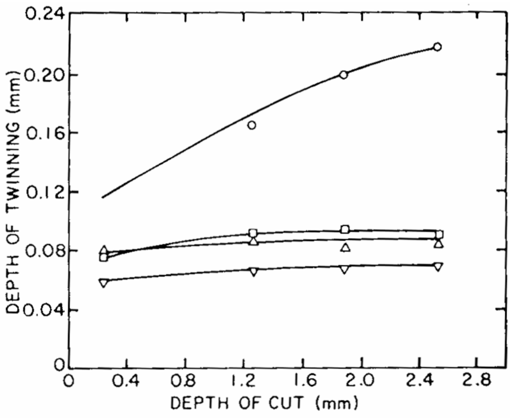


Figure VI-5. Influence of lathe-cutting depth and machining temperature on the depth of twinning in hot-pressed beryllium: ○—ambient temperature; □—230 °C; △—290 °C; ▽—340 °C.[AW]

Machining damage can be minimized by adjusting the machining schedule to produce finer and finer successive cuts. For example, each cut should be one-half of the depth of the preceding cut. The optimum schedule for a particular case would be determined by pre-evaluations. Cut depths can range from 12.7 μm (0.0005 in.) to nearly 9 mm (0.35 in.) if required.[36, 37] When finishing, cut depths should not exceed 0.76 mm (0.030 in.) to avoid developing excessive residual stresses. An example of a partial final sequence of finishing cuts was given as: 0.76, 0.51, 0.25, and 0.127 mm (0.030, 0.020, 0.010, and 0.005 in.).[35]

Hughes Aircraft specifies two procedures for finish machining of beryllium of hot-pressed blocks and wrought material, respectively, which includes stress relieving and surface-damage reduction, as follows:[45]

Hot pressed block

- Machine each surface to within 0.51 mm (0.020 in.) of final dimensions, using 0.76 mm (0.030 in.) maximum cut depths.
- Stress relief by heating at a rate not exceeding 316°C/hr. to 871 °C (vacuum or inert atmosphere). Hold one hour plus an hour for each additional 25.4 mm (inch) of thickness. Cool to 371 °C at a rate not exceeding 38 °C/hr. While still in furnace (vacuum/inert), cool to ambient at a rate not to exceed that obtained in still air.
- Machine each surface to within 0.25 mm (0.010 in.) of final dimensions, using 0.25 mm (0.010 in.) maximum cut depths.

- Machine each surface to within 127 µm (0.005 in.) of final dimensions, using 127 µm (0.005 in.) maximum cut depths.
- Etching after any machining step, if necessary.

Wrought products

- Machine each surface to within 0.43 mm (0.017 in.) of final dimensions, using 0.84 mm (0.033 in.) maximum cut depths.
- Machine each surface to within 0.18 µm (0.007 in.) of final dimensions, using 0.25 mm (0.010 in.) maximum cut depths.
- Machine each surface to within 51 µm (0.002 in.) of final dimensions, using 127 µm (0.005 in.) maximum cut depths.
- Etching after any machining, step if necessary.

There will be some degree of uncertainty as to the form of damage that may be present. Some published examples relating appearances to the extent of damage are presented here.[40] Visual inspection (naked eye or low magnification) should reveal some aspects of damage from the surface condition. A change in surface finish from a satin-like appearance for light machining damage (0.05 mm depth) to becoming striated with heavier damage, the degree of which increases with increased depth of damage, was reported for lathe turning of beryllium. Under optical or scanning-electron microscopy, surfaces with shallow twinning (0.04 mm depth) displayed a grain-like structure, whereas, surfaces with deep twinning (0.11 mm depth) revealed a smooth, smeared surface with shiny tool marks. If direct metallographic observation of the as-machined surface is difficult, replicas of the surface can be used and taken at several stages during machining. In lathe turning, it was observed that a change in twin depth was accompanied with a change in chip appearance. Also, the amount of tool wear (breakdown) was proportional to the degree of surface damage.

The most reliable method for evaluating the extent of surface damage is by metallographic examination of cross sections perpendicular to the surface. Care must be taken to remove any damage caused by the sectioning. A uniform amount of twinning across a section, especially extending beyond a reasonable machining-damaged depth, would be indicative of this. Additional evaluations may be made such as residual stress measurements, ultrasonic surface-wave measurements, and x-ray diffraction for surface textures. However, surface damage could exist without positive results from these observations. It should be noted that although machining damage can form without the presence of cracks, other forms of damage are probably always present when cracks are present.[40]

## VII. Machining Operations

Machining encompasses a number of different operations: turning, milling, drilling, boring, grinding, sawing, abrasive cutting, thread cutting, chemical machining, electrical-discharge machining (EDM), electrochemical machining (ECM), and trepanning. Feed rates and cutting speeds in lathe turning and milling are comparable to those used in machining cast iron, although they may be dictated by the efficiency of the dust-extraction and chip-collection systems. To avoid damaging the relatively soft beryllium, soft chuck jaws should be used, providing as large a contact area as possible. Because of its relative softness, a positive rake angle is recommended for all beryllium machining. Soft materials have a tendency to puddle up in front of the cutting tool, which is minimized by having a positive rake angle.

Beryllium is usually machined dry when heavy stock-removal operations are performed. Coolants are used for operations such as deep-hole drilling, threading, and/or where close tolerances, damage-free surfaces, and long tool life are required. When machining with a coolant, and using brass or copper fixtures, the possibility exists of developing a galvanic action between the beryllium and the fixtures, and this possibility should be monitored.[35] Sulphurized and chlorinated oils should be avoided because they corrode or discolor the beryllium. When cutting fluid is used. the beryllium must be thoroughly washed in Stodard or MEK solvent and dried after machining. Wet cutting helps in suppressing the beryllium dust, but increases the cost of reclaiming the beryllium scrap.

In a document on specifications for machining beryllium, rough machining (turning, milling, and boring) shall be performed to within 1.27 mm (0.050 in.) of the finished surface and to within 2.54 mm (0.100 in.) on a diameter.[45] Roughing cuts by sawing shall not be closer than 2 mm (0.080 in.) to the final surface. A 0.76-mm (0.30 in.) minimum cut shall be made on a mill or lathe prior to finish machining when roughing by sawing or with an abrasive cut-off wheel. Finish machining shall be defined as the removal of the final 1.27 mm (0.050 in.) of metal in order to meet dimensional requirements.

## VII-1. Turning

Turning is a machining process for generating external surfaces of revolution by a cutting tool on a rotating workpiece. The operation, which is usually performed on a lathe, includes producing thread forms, trepanning, facing, and in some cases, drilling and boring. Examples of some of the basic turning operations are shown in Figure VII-1-1.[46]

Best turning results are obtained with a positive back-rake angle from 1 to 5 degrees. Small positive or even negative rake angles are used for abrasive materials. The rake angles define the relationship between the cutting edge and workpiece. It is generally recommended that for most materials positive-rake angles be used with high-speed-steel cutters and zero or negative rake angles for carbide-tipped cutters. A positive rake angle will generally provide a better-defined edge than will a negative rake angle. A drawing illustrating the relationship between a single-point cutting tool and workpiece (at cutting edges) and the corresponding terms used are shown in Figure VII-1-2.[45]

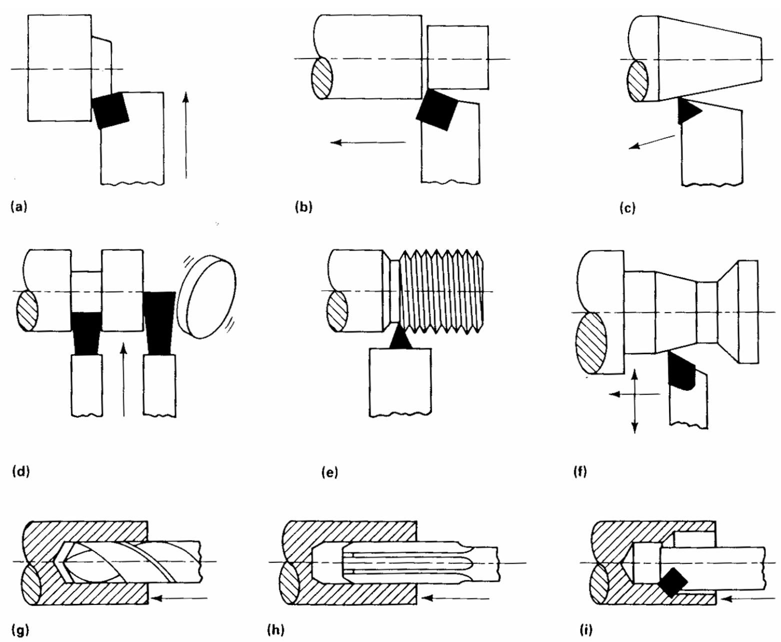


Figure VII-1-1. Some Basic operations performed on turning equipment: (a) facing, (b) straight turning, (c) taper turning, (d) grooving and cutoff, (e) threading, (f) tracer turning, (g) drilling, (h) reaming, and (i) boring; cutting tool in black.[46]

Single point tools must have sharp cutting edges, with a primary clearance angle of about 6 degrees and a secondary clearance angle of about 10 degrees.[35] It was suggested that for maximum metal removal, use zero rake and minimum side clearance. The latter is important to prevent pulling out metal and chipping the machined surface.[40] To reduce cutting pressure, and thereby minimize potential damage to the beryllium part, the nose radius or chamfer should be as small as feasible; a radius of 0.4 mm (1/64 in.) is recommended. Side cutting angles up to 45 degrees would protect faces from chipping when entering or leaving the workpiece.[37] Carbide tools should be used with the straight–tungsten grades being the best. Because of the abrasiveness of beryllium, live centers should be used.[33]

Beryllium is commonly rough turned, faced, and bored at speeds of 53.4 to 76.2 m (175 to 250 ft.)/sec. Speeds of 30.5 to 61 m (100 to 200 ft.)/sec. are recommended for finish turning of critical dimensions. Roughing feeds of 158 to 316 μm (0.006 to 0.012 in.)/rev. are generally used, with finishing feeds as low as 12.4 μm 0.0005 in.)/rev. Surface roughness would generally be in the ranges of 70 to 125 and 30 to 60 RMS, respectively.[35] Interrupted cuts should be avoided in turning a round part from a square blank. The use of non-coated inserts having a generous nose radius have been used successfully for roughing cuts. Cut depths could exceed 6.35 mm (0.250 in.) in some cases. Chipping, which may occur as the tool leaves the work at the end of a cut, can be avoided by taking light cuts, using a sequence of short finishing cuts at alternate ends, chamfering both ends prior to turning, and/or using run-off material.

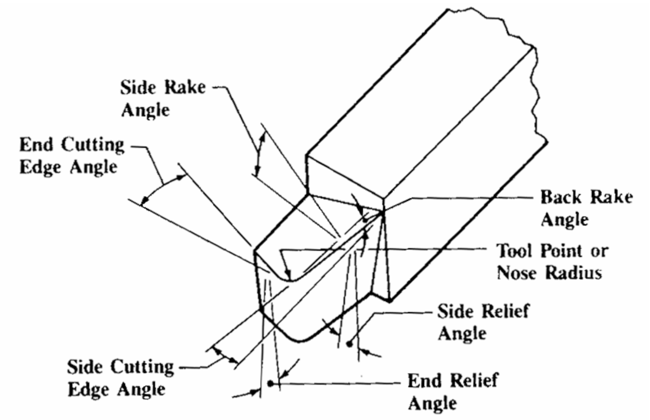


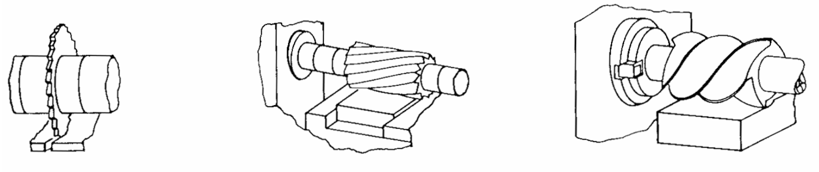
Figure VII-1-2. Terms applied to single-point turning tools. The side rake angle shown is positive.[47]

## VII-2. Milling

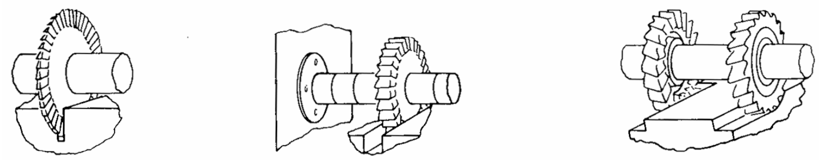
Milling is a machining operation in which metal is removed by a rotating multiple-tooth cutter whereby each tooth removes a small amount of metal with each revolution of the spindle. Since both workpiece and cutter can be moved independently in more than one direction at the same time, surfaces having almost any orientation can be machined. Relatively small chips are formed with variations in thickness within each chip. Basic milling operations and cutters and various surfaces that can be generated are illustrated in Figure VII-2-1.[48] Milling can be done in almost any type of machine that can rigidly hold and rotate a cutter while allowing a workpiece to be fed into the cutter (or visa versa).

Practices for milling are similar to those used for turning beryllium. Up-cut (climb) milling is recommended rather than the more-conventional down-cut milling in order to obtain the best surface finish, and maximum cuter life.[36] Edge fracturing (chipping), called “break-out”, can occur when the cutter moves against and out of an edge of the workpiece. To minimize the tendency to such chipping, up-cutting should be used during the roughing stages, which can be followed by conventional cutting using backup plates (free-cutting steel, Plexiglass, or beryllium). By beveling (chamfering) the edges of the workpiece, a more gradual exit is provided for the cutter, thereby, also reducing the tendency for break-out.[35] Milling parameters may be affected by chip-collection problems as it can be difficult to position the collection piping to the cutter, which is immersed in the workpiece. Thus, except for small vertical-type machines, milling machines are customarily completely enclosed in a glove-box.[36]

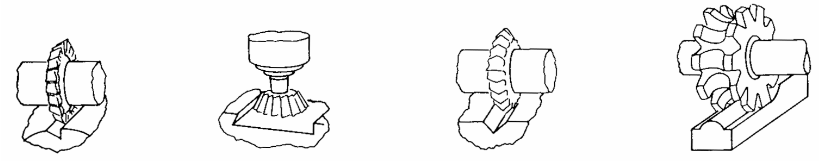
The axial rake, radial rake, and corner angle in milling are respectively equivalent to back rake, side rake, and side-cutting-edge angle in turning. These angles are usually used to define the relationship between the cutting edge and workpiece. The rake angle affects the shear angle in the chip-forming process and greatly affects the tool force, power requirements, and temperature generated. The tool force decreases as the true rake angle becomes more positive. Face-milling cutters with fine pitches and positive radial and axial tooth rakes should be selected for beryllium. Milling cutters with blade-type inserts can be useful with many variations of blade angles. Carbide insert-type cutters with 30 to 45 degree corner chamfers or 0.76 to 1.04 mm (0.030 to 0.040 in.) radii are recommended.[35] Interrupted cuts should be avoided; instead, when possible, interrupted cutting should be performed using turning operations.[37]



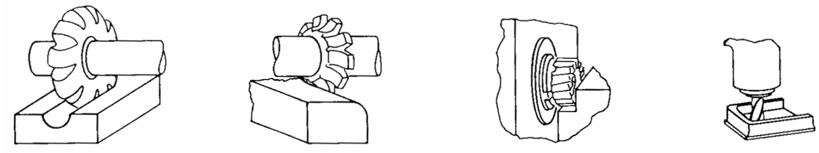
(a) Saw, slitting (b) Plain (c) Helical, plain



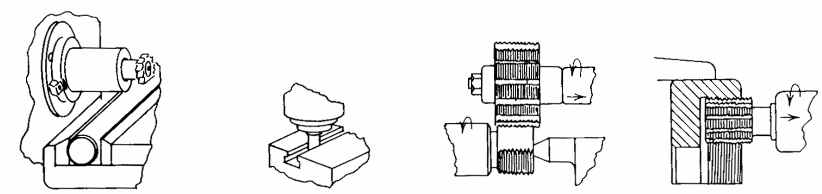
(d) Saw, slotting (e) Side mill, slotting (f) Half-side, straddle



(g) Single angle (h) Single angle (i) Double angle (j) Concave



(k) Convex (l) Corner rounding (m) Shell end (n) End



(o) Key seat (p) T-slot (q) Male thread (r) Female thread

Figure VII-2-1. Basic milling operations and cutters illustrating the variety of surfaces and surface combinations that can be generated.[46]

***Face milling*** generally uses cutting speeds in the range of about 50 to 90 m (164 to295 ft)/min. and feed rates of 76 µm to 127 µm (0.003 to 0.005 in.) per cutting tooth. Finishing cut depths of from 127 to 254 µm will usually yield an acceptable finish.[36] Brush Wellman states that beryllium is usually rough milled at surface speeds of 30.5 to 45.7 m (100 to 150 ft.)/sec. with a feed rate of up to 0.254 mm (0.010 in.)/tooth and a maximum cut depth of 6.35mm (0.250 in.). Finish milling would occur at 45.7 to 61 m (150 to 200 ft.)/min with a maximum cut depth of 762 µm (0.030 in.) and a feed rate of 76 to 203 µm (0.003 to 0.008 in.)/tooth.[35] (There is some inconsistency in the data from the two references.)

Programming to eliminate exit edge milling will reduce the tendency for edge damage. Chamfering the edges of the workpiece prior to final milling will also reduce edge damage. The most common method to avoid the edge problem is to cut into a backing plate.[36]

***End milling*** generally uses cutting speeds in the range of about 23 to 54 m (75 to 177 ft.)/min. and feed rates of 0.127 mm (0/005 in.) per cutting tooth, the particular parameters being influenced by the exit-edge conditions. Unless special precautions are taken to avoid the tendency of rubbing with shallow cuts, (causing surface damage), finishing cuts should be limited to depths of 127 to 254 µm. Unless provided with rigid spindle construction, end-milling cuts should be limited to 3.175 mm (0.125 in.).[36] More flutes, rather than fewer flutes, are recommended for end milling.[35]

***Roller or slab milling*** generally uses cutting speeds in the range of about 15 to 24 m (50 to 80 ft.)/min. and feed rates of 76 µm to 127 µm (0.003 to 0.005 in.)per cutting tooth. This milling method is often most effective for finishing as it does not present a trailing-edge problem. The rigidity in the arbor or fixturing necessary to avoid rubbing cannot be achieved with very shallow cuts. Thus, cut depths are limited to a minimum of 51 µm (0.002 in.). However, it was found that for correct feeds, twin damage was less than 51 µm (0.002 in.) for roller-milling cuts in the 254- to 305-µm (0.010- to 0.012-in.) range.[36]

## VII-3. Drilling

The basic motions of drilling consists of a relative rotation between the workpiece and tool, along with a longitudinal feeding. These two motions also occur in many other machining operations. Consequently, drilling can be done on a variety of machines. Drill presses are specifically designed for drilling operations with a number of different types of presses available for different drilling operations. The basic requirement is that the spindle (or spindles in a multiple-spindle drilling machine) must rotate accurately and resist any side forces introduced by the drilling. Drilling of long holes offers special problems not generally encountered in typical drilling operations. As the hole length increases, it becomes increasingly difficult to support the workpiece and the drill properly. Rapid removal of the chips, which is necessary to assure accurate drilling, becomes more critical with increased hole length. Deep-hole drilling machines were developed to overcome these problems. Dissipation of heat also becomes a problem. Hole depths greater than five times the diameter are considered to be deep holes. The heat problem with deep holes is addressed by using cutting fluids under pressures up to 20.7 MPa (3,000 psi) with oil holes or rifle drills.[35] Feed rates for beryllium are generally kept between 25.4 and 254 µm (0.001 and 0.010 in.) per revolution. Cutting speeds range from 7.6 to 30.5 m (25 to 100 ft.)/min., with the higher range being most common. A rigid setup is important for dimensional control and minimization of potential drilling damage. In setups lacking sufficient rigidity, drills with short flutes and tapered shanks should be used.[36] Cutting speeds were also given as 7.6 to 45.7 m (25 to 150ft.)/min. with speeds at the lower end of the range for most applications.[35] Feed rates varied from 15 to 30 µm (0.0006 to 0.0012 in.)/revolution, and in special cases may be as high as 254 µm (0.010 in.)/revolution. Prior center drilling is advisable to minimize a bouncing entrance that may cause chipping and, in thin parts, a breakthrough.

The major difficulties with drilling beryllium are tool wear, hole-surface damage, chipping, and lamellar cracking or spalling as the drill breaks through the workpiece. The latter can occurs when drilling rolled sheet having a high degree of anisotropy (crystallographic preferred orientation). Hole chipping on breakthrough can be minimized by using a backing plate. Beryllium, being notch sensitive, if highly stressed, may stress relief itself by intergranular cracking. Thus, it is important that drilling parameters, especially feed rate and having the proper drill point[9], are chosen to minimize machining stresses.[36] Pilot holes should not be used, as enlarging holes by successive drilling can lead to hole damage. For large-diameter holes, final sizing should be performed by boring, which also removes hole-surface damage introduced by drilling.[36]

A slight taper from drill point to shank is important to minimize the resistance due to abrasive wear.[37] For deep holes, tapering in from the drill tip to the shank by about 100 µm will reduce heat generation and abrasive wear.[35] Drills with thinned webs are used to reduce thrust force. For through holes, the corners at the outside diameter and the drill point should be chamfered at a 45-degree angle to prevent chipping when breaking through the beryllium.[37] The web thickness should be thin at the drill point and gradually enlarged for strength and rigidity. Two-fluted-tipped drills of tungsten carbide with included angles between 90 and 120 degrees are commonly used. Brush Wellman recommends using an automatic torque-sensing drilling device[m], which varies the speed and feed rate in order to maintain the cutting force within safe limits for both drill and beryllium.[9] A dull or chipped tool will indicate an increased force and thereby reduce the feed rate.[35]

Boring involves the use of a single-point cutter whereby an internal-diameter surface is generated relative to the centerline of the rotating spindle. It is a process used primarily for enlarging or finishing holes. Boring is also used for circular contours other than holes.

According to specifications by Hughes Aircraft for EDM drilling of beryllium, the metal-removal rate for rough cutting should not exceed 18.0 cm$^3$ (1.10 in.$^3$)/hr. and cuts should not extend any closer than to within 0.102 mm (0.004 in.) from finished surface. The metal-removal rate for finishing cuts should not exceed 2.05 cm$^3$ (0.125 in.$^3$). The final last finishing cuts prior to a stress-relief treatment should consist of a minimum of 0.102 mm (0.004 in.) of metal removal.[45]

### VII-4. Grinding

Surface grinding is usually not recommended for bulk-metal removal of beryllium. It is primarily used to achieve extremely close tolerances, a very fine surface finish, and/or where sharp edges are required. If machining dry, the glove box must be completely dry to contain the fine powder. As with many metal powders, the fine powder can be pyrophoric since sparks may develop during the grinding. Because of these problems, grinding of beryllium should be performed wet.

The following recommendations were presented as a guide for grinding beryllium:[36]

- Use a high-cutting surface speed of 150 to 2000 m (500 to 6500 ft.)/ min.
- Use a high work speed of 6.1 to 18.3 m (20 to 60 ft.)/min.
- Use a low cross-feed rate of 1.52 mm (0.060) in./pass.
- Use a small cut depth of 0.025 to 0.076 mm (0.001 to 0.003 in.)/pass for rough grinding and 2.5 to 12.7 µm (0.0001 to 0.0005 in)/pass for finishing cuts.
- For rough grinding, use a tough-grained, aluminum–oxide wheel having a course grain and a soft vitrified bond similar to Norton 38 A46-K5 or A46-K5-VBE.

---

[m] “Tornetic Drilling Unit” by Dyna Systems, Inc. of Torrence CA

- For finish grinding, use sharp-grained, silicon-carbide-type wheel having a medium grain (40 to 80 grit), soft to medium hard similar to Norton 38 A60-K5-VBE or 37046-K + VK.
- Allow frequent dressing of the wheel to prevent buildup that inhibits the process from being speeded up.
- Use water-soluble oil emulsion, free from sulfur or chlorine when coolant is required, and ensure that parts are cleaned and given a surface neutralizing treatment using perchloroethylene after machining is finished.
- Side wheeling should be avoided.

## VII-5. Sawing (Cutting)

Cutting of beryllium blocks into sizes suitable for machining operations is usually performed by either band sawing, mill sawing, elastic-wheel slitting, or electric-discharge sawing. Headers are removed from cast ingots using either band or mill sawing. Rolled plate and sheet are cut into workable sections using either band sawing or elastic-wheel slitting. Cutters must be kept in sharp condition. In general, lack of sharpness and/or too few teeth can result in severe machining damage.

***Band-sawing*** (surface) speeds vary from about 61.0 m (200 ft.)/min. for thin sheet to 30.5 m (100 ft.)/min. for thick-section blocks. The corresponding feed rates vary from 1290 $cm^2$ (200 in. $^2$)/min. to 6.45 $cm^2$ (1 in. $^2$)/min.[36] Saw-blade widths should be increased as the workpiece thickness is increased. Band widths of 6.35 mm (0.25 in.), 12.7 mm (0.5 in.), 25.4 mm (1 in.), and 50.8 mm (2 in.) are typically used for thicknesses of 0.635 mm (0.025 in.), for up to 3.17 mm (0.125 in.), for up to 76.2 mm. (3 in.), and for up to 76.2 cm (30 in.), respectively. Generally, the greater the number of teeth the smoother the cut; however, the chance of clogging up the spaces between the teeth correspondingly increases. With hot-pressed powder, it is best to use blades having fewer teeth, in the range of 4 to 10 teeth per 2.54 cm (in.) to avoid such clogging. Thin sections should use blades with a lower teeth spacing of 20 to 30 teeth per 2.54 cm. (1 in.).

***Mill sawing*** (surface) speeds are in the range of about 30.5 to 45.7 m (100 to 150 ft.)/min. Since the operation can be easily performed without the use of coolants, it offers a high recoverable, low-contamination yield of swarf for recycling. Machining conditions are similar to milling. Cut depths of up to 6.35 mm (0.25 in.) are allowable.[36]

***Elastic-wheel slitting*** exhibits similar characteristics as those shown for surface grinding. A typical wheel is the Norton A60-QET. The main advantages over other sawing techniques are that it causes less machining damage to the beryllium and does not create the same problems with breakout and burring. The elastic-wheel saws can have widths as small as 0.635 mm (0.025 in.).

***Electrical-discharge sawing*** involves having a conductive electrolyte sprayed through nozzles into the space between the beryllium workpiece (anode) and a continuous moving band of strapsteel (cathode). A blade-shaped electrode moves at about 20 m (65 ft.)/sec. and is fed towards the workpiece by a control system that maintains the proper arcing and prevents welding between the two electrodes. Feed rate is controlled to maintain successive arc discharges, each one to last about 100 µsec. Sawing rates are approximately 19.4 $cm^2$ (3 in.$^2$)/min. with cut widths of about 0.8 mm (0.032 in.) A thinner, smoother cut with a lower stressed surface is achieved compared to that obtained using a comparable mechanical saw. The residual stresses are still sufficiently high as to require a final finish machining to eliminate any microcracks that may have developed. The process is best used for rough cutting.[36]

***Abrasive sawing*** technique is suggested for obtaining straight cuts of beryllium sheet using an abrasive sawing technique.[9] The operation is performed wet using a resin-bonded, semi-friable aluminum-oxide wheel rotating to give a surface speed at 35.6 to 45.7 m/sec. (7000 to 9000 ft./ min.). A wheel with an abrasive grain size of 80 grit and a relatively soft "L" bond grade is recommended.

## VII-6. Thread Cutting

Threading beryllium is usually done with a single-point tool. Due to its brittleness, care must be taken to avoid chipping both during and after thread cutting beryllium. Machining external-truncated threads or by drilling oversize holes on internal threads, thereby increasing the crest of the thread, reduces the chipping hazard. A 55% effective thread depth is recommended to develop a sufficiently wide crest.[36] The tool angle should be so that only one side of the thread at a time is roughed out. For the final finished cuts, the cutter should be fed straight in, in order to finish both sides of the thread simultaneously. Fine cuts are to be made throughout the threading operation.[36]

## VII-7. Cutting Speeds and Feed Rates

Among the factors that affect cutting speeds and feed rates are: chip-collection and dust-elimination systems, metal-removal rate, tool-wear rate, surface finish, and component size.[36] Replacing a tool may be required in order to maintain a good surface finish. This can cause problems with dimensional tolerances. Increasing feed rate and reducing surface-cutting speed was shown to improve tool wear. Increased feed rate, however, degrades the surface finish, which can be subsequently improved by etching (if a small loss in dimensional tolerance is acceptable). Normal finishes are in the range of 0.76 to 1.52 μm (30 to 60 μin.) rms. Etching machined finishes that were in the range of 1.01 to 2.29 μm (40 to 90 μin.) yielded surface finishes in the range of 0.89 to 1.14 μm (35 to 45 μin.) rms. Feed rates used ranged from 50.8 to 381 μm (0.002 to 0.015 in.) per revolution and surface cutting speeds ranged from 0.38 to 5.08 m/sec. (75 to 1000 ft./min.). Cut depths can range from 12.7 μm to 8.89 mm (0.0005 – 0.35 in.).[36]

## VII-8. Electrical-Discharge Machining (EDM)

Electrical-discharge machining is a method of metal removal by erosion from sparks, which are created between the workpiece and a shaped electrode (usually a graphite, copper, or brass cathode) using a pulsed-power supply. In using a low mechanical-support force and avoiding any tool-to-workpiece contact, EDM lends itself to precision machining of intricate shapes, fragile, thin-walled components, narrow deep slots, small holes, and trepanning. The sparks travel through a dielectric fluid (which also acts as a coolant) at a controlled distance. Excess heat, however, can cause surface melting and resolidification, alloying with the electrode material, and microcracking, resulting in a defective surface as much as 127 μm deep. This damage can be minimized by operating at low current levels, high frequencies, and low metal-removal rates. A cutting rate of 6.45 $mm^2$ (0.010 $in.^2$)/min. can be achieved with a brass electrode, providing a smooth surface finish of 0.25 to 0.51 μm (10 to 20 μin.) RMS on beryllium.[36] Low residual stresses are obtainable. An example for having a distortion-free mirror was given where the only stresses following EDM were due to those in the original part.[37] High cutting rates result in rough surfaces with numerous microcracks of up to a depth of 0.13 mm and in relatively high residual stresses.[40]

The EDM process is claimed to be very effective and practical for machining small features, and otherwise inaccessible areas as well as intricate, irregular, and complex curved shapes of beryllium at good production rates. A modified EDM method for cutting beryllium with close tolerances consists of having a thin traveling-metal wire, usually a copper-based alloy, as the electrode (wire EDM machine).[9, 13] A thin loosely adherent copper residue from the wire can be left on the as-machined surface, which can be removed by a flash etch with nitric acid.[13] Etching EDM beryllium surfaces resulted in slightly better tensile properties than those obtained prior to etching.[44] Since the EDM process may create additional beryllium-recovery problems, alternative methods for machining beryllium should first be considered.

According to specifications by Hughes Aircraft for EDM drilling of beryllium, the metal-removal rate for rough cutting should not exceed 18.0 $cm^3$ (1.10 $in^3$.)/hr. and cuts should not extend any closer than to within 0.10 mm (0.004 in.) from the finished surface. The metal-removal rate for finishing cuts should not exceed 2.05 $cm^3$ (0.125 $in^3$)/hr. The final last finishing cuts prior to stress relief should consist of a minimum of 0.1 mm (0.004 in.) of metal removal from a surface.[45]

## VII-9. Electrochemical Machining (ECM)

Electrochemical machining (ECM) refers to the controlled removal of metal by anodic dissolution in an electrolytic cell in which the workpiece is the anode and the tool is the cathode. The electrolyte is pumped through the space (cutting gap) between tool and workpiece, while direct current is passed through the cell at a low voltage to dissolve metal from the workpiece. Electrolytes are usually aqueous solutions of inorganic salts.[49] Sodium nitrate and sodium chloride are electrolytes that have been successfully used for beryllium.[9] Electrodes are usually copper, brass, or stainless steel. The current can range from 50 to 20,000 A, with a current density of 0.155 to 3 1 A/$mm^2$ (100 to 2000 A/$in^2$) and 30 V dc applied across a gap of 0.025 to 1.27 mm (0.001 to 0.05 in.) between the tool and workpiece.[49] The electrolyte flows through the cutting gap at a rate of 30.5 to 61 m (100 to 200 ft.)/sec. A schematic of an ECM system is shown in Figure VII-9-1.[49] Modifications of the cleanup system would be expected for the recovery of the dissolved beryllium and any suspended beryllium solids.

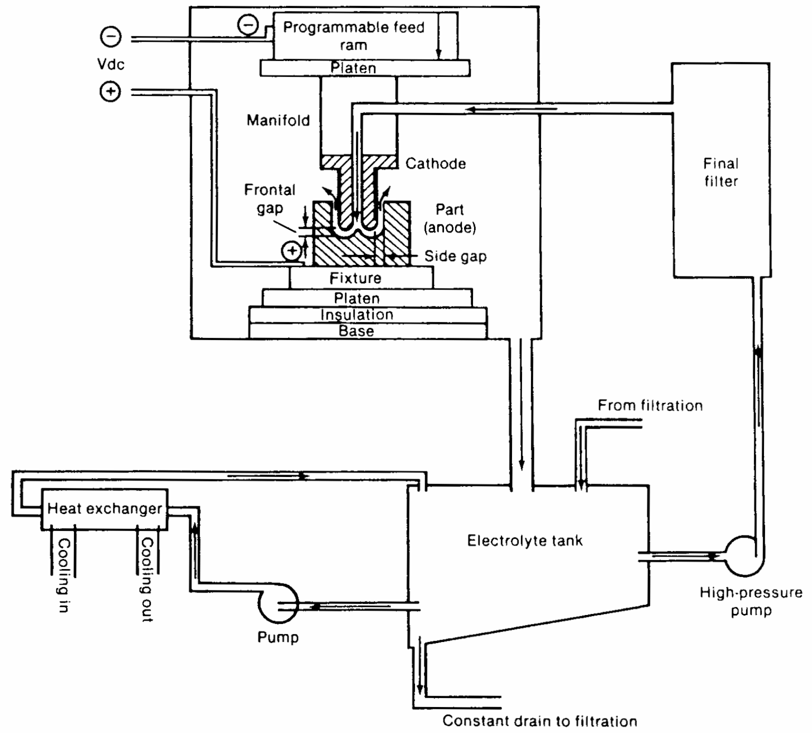


Figure VII-9-1. Schematic of an electrochemical machining system, which is applicable to most metals.[49] (Modifications of the cleanup system would be expected for recovery of beryllium).

The ECM process has successfully been used for a number of years for trepanning, contouring, slotting, and drilling of complex beryllium parts.[36] It produces only a relatively small degree of surface damage.[9] The beryllium machined surfaces are free of twins, microcracks, and other defects, and rapid machining rates can be achieved. To prevent corrosion following ECM, parts should be rinsed in deionized water and given a light etch to remove traces of salt from surfaces. To further reduce any corrosion tendency, the parts may then be immersed in a water-soluble oil, such as may be used as a coolant during mechanical machining.

## VII-10. Electrochemical Grinding (ECG)

Electrochemical grinding (ECG) is a modification of ECM, in that the metal is removed by a combination of electrochemical action and mechanical abrasion. In applying ECG to a beryllium rod, although the surface was found to be free of any metallurgical-related damage, the process caused a slight roughening of the surface.[40]

## VII-11. Chemical Machining

Chemical machining refers to removal of metal by chemical dissolution (etching) with several possible objectives: removal of machining-damaged surfaces, thinning sections to reduce weight, and/or producing detailed precision parts. The typical etching solutions for beryllium are sulfuric acid, nitric acid-hydrofluoric acid mixture, and ammonium biofluoride. Additional etchants are reported in section VI. There are two main types of processes: chemical milling (machining) and photochemical machining; the latter process is used for small details, especially where high precision is required.

***Chemical milling*** has been successfully used in the fabrication of parts made from beryllium block, sheet extrusions, and forgings. Metal removal may be over the entire surface or it may be restricted to selected areas by masking. Chemical milling may be used to remove damaged surface layers and/or to reduce weight by restricting etching (thinning) to specific areas. Thin uniform distortion-free webs can be obtained.[33] Masking may also be used to develop certain designs. The removal of damaged surfaces is typically performed by complete immersion in the etchant. As the etching is unlikely to be uniform throughout the part, such immersion may compromise any high tolerances obtained by a previous machining operation, especially for complex designs. Careful control of the etching could uniformly remove metal from all surfaces.[33] Surface finishes are generally rougher after chemical milling, depending to a great extent on the prior-surface condition.

The maskants[n] are specially designed liquid elastomers, which, when cured, are hand strippable and resistant to the etchants. The procedure used is as follows: The cleaned, dried workpiece is coated with the liquid elastomer, which is then dried and cured. A pattern is scribed on the cured elastomer defining the boundaries between the areas to be etched and unetched. The mask is then peeled off from the etchable areas and the part immersed in the etchant for a specific period of time. If a differential amount of thinning is required, a new pattern may be scribed on the remaining mask, or a new mask may be applied over the etched areas and scribed with the pattern. The appropriate parts of the mask are peeled off and the part is again immersed in the etchant. This gives two sets of areas with different amounts of thinning. The process can be repeated a number of times on the same part. The maskants can be applied either by immersion in the liquid elastomer or by using hot-airless-spray equipment. The maskant must be cured to provide the proper amount of adhesion; too low adhesion results in poor definition between etched and unetched regions; excessive adhesion makes stripping difficult. Curing can be done at temperatures from ambient up to over 90$^{O}$C; increasing temperatures results in better adhesion as well as shorter curing times.[50] Material removal rates by the etchant vary from 25 to 51 µm (0.001 to 0.002 in.)/min. Tolerances of the final part can be very close to those obtained prior to etching and can be held to ± 127 µm (± 0.005 in.), and may vary in complex configurations.[9]

***Photochemical machining (PCM)*** is a metal-etching process that uses a photoresist maskant to define the location where the metal will be etched. The photoresist can be applied by dipping (immersion), whirl coating, or spraying.[51] Whirl coating yields the best uniformity, while spraying provides the most versatility. The resists are dried at ambient temperature and then baked for about 15 min. at 120$^{O}$C. or at ambient temperature for longer periods of time. The photoresist can also be applied as a solid dry film laminated to the part. However, this provides poorer resolution than that of the liquid form. The photoresist mask provides a photosensitive surface that is resistant to the etchant. Etchants used for chemical milling of beryllium are also used for PCM. The PCM process is used to produce detailed precision parts. Best results are obtained on flat material of uniform thickness and having a fine grain size. Thicknesses can range from 0.013 to 1.5 mm. (0.0005 to 0.06 in.).[51] Very tight tolerances are attainable with beryllium: ± 0.075 mm (± 0.003 in.) is easily attainable; ± 0.025 mm (± 0.001 in.) can be achieved if required.[38]

---

[n] Elastomer coatings (masks) deposited on areas that are not to be attacked by the etchant.

A photochemical flow chart of the process is shown in Figure VII-11-1.[51] Basically, the steps are as follows: doing the pattern artwork, making the masters, preparing the workpiece, applying the photoresist, covering the workpiece with the masters, and imaging and developing such that the pattern (detail) is defined by the photoresist. The photoresist that was exposed to the imaging light is washed away by the developing solution and subsequently will be attacked by the etchant. Alternatively, the unexposed photoresist can be made to be washed away, the methods are referred to as "positive" and "negative" masking, respectively. The masters are reusable, thus providing highly reproducible details in production parts. Various materials and techniques can be used for the artwork and masters, depending on the required precision and dimensions of the details and the desired permanency of the masters. For example, the original artwork may range up to 200 times actual size and photographed with a reduction camera. The artwork may be done manually or by computer-aided drafting.[51]

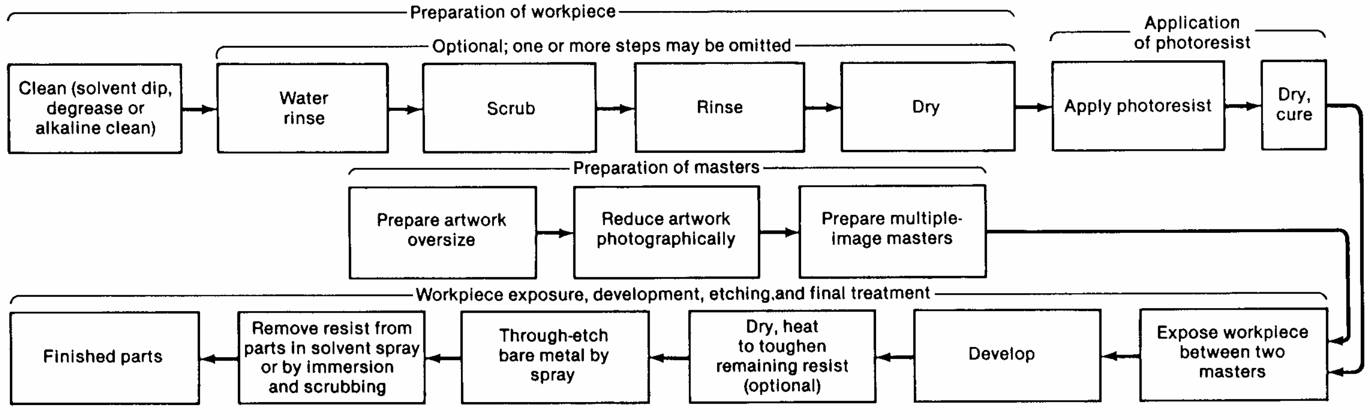


Figure VII-11-1. Flow chart of principal process steps for photochemical etching.[51]

## VII-12. Trepanning

Trepanning allows recovering the cost of part of the material and avoids the cost of reprocessing machining chips. It is a machining process for producing a disk, cylinder, or tube from solid stock or for producing a circular groove or hole in the stock. This is accomplished by having a tool containing one or more cutters (usually single point) revolving around a fixed center. Part depths (thicknesses) would decrease with increase in part diameter. The unused material, such as a cylinder formed by trepanning a hole, would be available for making some other part or used for higher value scrap.[52] Holes over 25.4 mm diameter in beryllium are usually trepanned rather than being drilled or bored.[36] A set-up for trepanning a disk is depicted in FigureVII-12-1.[52] The set-up contains an adjustable fly cutter mounted on a twist drill, which serves both as driver and pilot. Having the pilot (drill) on the drive unit helps to stiffen the tool, reduce chatter, and retain cutter sharpness. A hole is formed in the center of the disk. If a hole is not acceptable, the drill pilot is replaced with a drill-free pilot, however, providing less rigidity and possibly more tool chatter and some loss of dimensional control.[52, 36] In trepanning, the cutting or parting blades must be designed with proper clearance angles to give optimum cutting, and must be kept sharp, if not, it is replaced or severe machining damage may occur. Replacing the tool may cause problems with dimensional tolerances. Cutting-edge clearance should be contoured to the outside and inside diameters with zero to positive rake and a 3-to-5-degree end clearance to be most effective and to reduce tool wear.[36, 37]

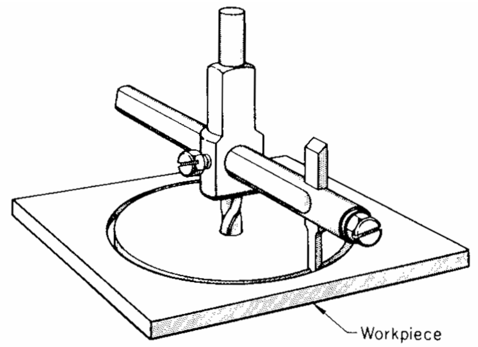


Figure VII-12-1. Drill-mounted, adjustable fly cutter used for trepanning various sizes of disks from flat stock. It can also be used for forming grooves around centers grooves.[52]

### VII-13. Tapping

Taps with two or three flutes are most effective. One should be aware of creep characteristics in beryllium, especially in thin cross sections. High-speed-steel taps should be surface treated, e. g., by nitriding. Lead-screw tappers with fine torque adjustments give the operator good control of tap behavior. A minimum of 1.59 mm (1/16 in.) from an edge is required for tapping beryllium. Tapping lubricants should be used, preferably a sulfur-based oil.[37]

## VIII. Adhesive Bonding (Joining)

Adhesive bonding of beryllium permits utilization of a combination of desirable physical and mechanical properties of beryllium while minimizing the inherent problems of high notch sensitivity (especially at fastener holes when using mechanical fasteners) and low ductility.[9, 43] Joining a thin section to a thick section enables the full strength of the thin section to be utilized, which is difficult to achieve with mechanical fasteners. In addition, the adhesives produce a uniform load distribution over the bonded area, thus minimizing stress concentrations. It avoids distortions that would result with other joining methods. It allows the fabrication of complex shapes where other joining methods are not feasible. Adhesive bonding provides an assembly with lower weights than those obtained with mechanical fasteners. Properties of the adherents are not degraded. The adhesive reduces or prevents galvanic corrosion between dissimilar metals. Typically, adhesive bonding is used in applications where the structural strength requirements for shear are less than 35 MPa, temperatures are less than 235$^{O}$C, outgassing requirements are not stringent, and lack of heat transfer across the joint is acceptable. Because adhesive bonds are not inherently strong, designs should provide for an adequate surface contact area. Also, designs should account for their susceptibility to failure by peeling. It is often difficult to apply adequate inspection to adhesive bonds.

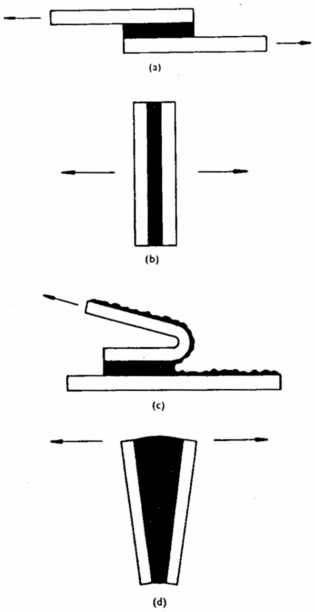


Figure VIII-1. Four important stresses to be considered in designing adhesive bonds: (a)—shear; (b)—tension; (c)—peel; (d)—cleavage.[53]

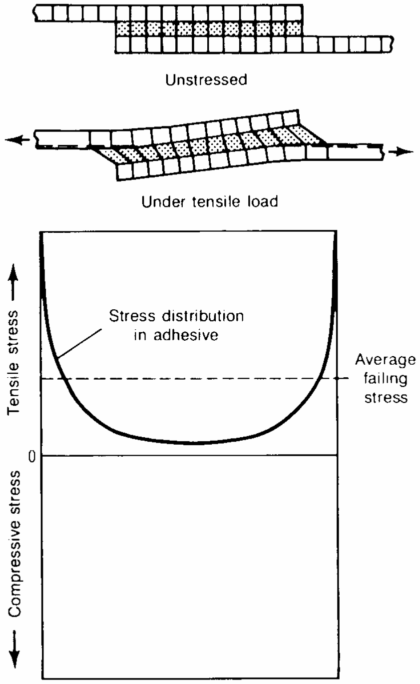


Figure VIII-2. Illustration of a non-uniform stress pattern introduced by a tensile load applied in shear to a plain lap joint.[54]

In the design of the joint and the choice of adhesive, the potential for localized stress concentrations that could be produced in service must be considered. The four most important stresses that could be present in adhesive bonds are illustrated in Figure VIII-1;[53] they are shear, tensile, peel, and cleavage.

Most adhesive joints are lap joints in which a non-uniform stress pattern can be induced by a tensile load applied in shear, as illustrated in Figure VIII-2.[54] Examples of various lap joints are shown in Figure VIII-3.[55] Some of the joints that are illustrated in this figure, such as the half-lap joint, ideally should result in a uniform stress pattern when under tensile-shear loading. Several of these joints, however, would involve additional machining. An extensive discussion with corresponding illustrations of adhesive joints is presented in reference 53.[o]

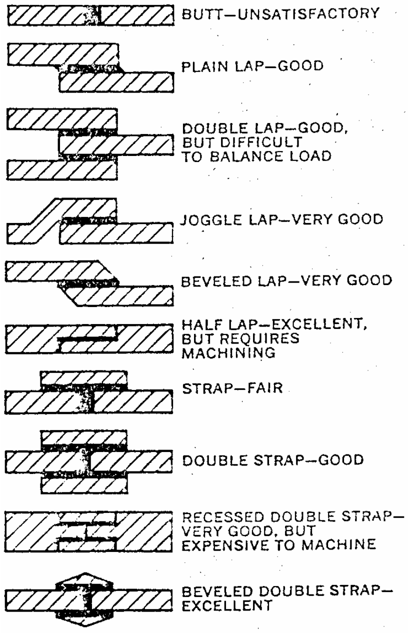


Figure VIII –3. Examples of possible shear-lap configurations.[55]

Differences in the temperature coefficient of thermal expansion (CTE) of the two metals being joined, the service temperature of the part, the cure temperature of the adhesive, and the transition temperature of the adhesive must all be considered. For example, the CTE of aluminum and its alloys is almost double to that of beryllium, while most steels have a value close to that of beryllium. (Values for the three materials will depend on their specific compositions and processing.) Thus, heating of an adhesive-bonded Be/Al structure may introduce a sufficiently high thermal stress to rupture the bond, whereas the Be/steel joint probably could have survived under the same conditions. Most adhesives are limited to an upper temperature of between 65 and 95 °C and some to temperatures up to 175°C. Several adhesives are available for limited use to 370 °C.[54] Depending on the application of the bonded structure, specific adhesives covering a range of temperatures are available.

The strength of an adhesive bond depends upon two elements, cohesion and adhesion. Cohesion is associated with the strength of the bonds between the various molecules of the adhesive layer. Adhesion refers to the strength of the bond between the adhesive and the substrates (adherents). As with metallic materials, the toughness or ductility of the adhesives can range between the two extremes of being ductile to being brittle. Stress concentrations at voids can significantly reduce the strength of an adhesive bond, especially in a brittle adhesive, leading to premature, brittle-like failures. Although the damaging effect of stress concentration at flaws (such as a bubble) in

---

[o] No attempt is made to educate the reader on the architecture (molecular structures) of adhesives. Many handbooks are available on the subject and several are referenced here.

a brittle material is obvious, there is some evidence that in some circumstances voids can toughen a ductile adhesive by involving larger volumes of the adhesive in plastic deformation during fracture. A study using a blowing agent to introduce voids into a polyethylene adhesive on copper showed that the voids resulted in a significant increase in peel strength. On the other hand, voids may also initiate crazing, which can grow, developing cracks leading to failure.[56]

Voids can readily form as a result of air entrapment during preparation of the adhesive as well as by failure to displace air from the substrate surface. The high viscosity of many adhesives in their liquid state makes the removal of air bubbles difficult, even when a vacuum is applied. Moisture, either in the adhesive or on the substrate surface, may also be a source for bubbles when the system is heated.[56] Although there is a range of non-destructive techniques for detecting defects, such as ultrasonics, holography, thermal-wave imagining, and x-radiography, small voids less than about several mm$^2$ in area cannot readily be detected (if at all) by these techniques.[56] The non-destructive detection (characterization) of defects is made especially difficult due to the thinness of the adhesive.

In some cases, a primer may be used or the characteristic of the surface may be modified to improve the performance of the bond. A primer is usually a dilute solution of an adhesive in an organic solvent.[55] It is applied following surface preparation and dries to a film thickness that can range from about 1.5 to 50 μm. One purpose of the film is to protect the surface from the environment, extending the life between surface preparation and adhesive application by as much as six months depending on the primer/adhesive system used. It is also used to increase the peel strength of structural adhesives. The primer can be dried at room temperature or force dried at 66$^{O}$C; this provides a non-tacky surface that can be protected from contamination and damage by either wrapping, sealing/bagging, or covering with a no-transferring adhesive-backed paper.[55]

## VIII-1. Classification of Adhesive Materials

There are a vast number of adhesive materials that are commercially available as well as extensive literature sources on this subject (For example, refer to references 54, 56, 57, 60). It was estimated that over 2500 different products were available.[55] The type of service stresses, joint design, environmental factors such as temperature and humidity, potential exposure to other vapors or liquids, performance reliability, biological inertness, flammability, special requirements such as electrical and thermal needs, and/or cost could determine the choice of adhesive. In this report, reference to specific adhesives will usually be made only with reference to the preparation, evaluation and/or application of adhesives. Adhesives specific for beryllium joints, however, will be presented.

Adhesives can be classified in a variety of ways. Benefits and limitations of various adhesive types are listed in Table VIII-1-1.[58] A classification of structural adhesives based on chemical type, which also contains cure temperatures, service-temperature ranges, and strength values, is shown in Table VIII-1-2.[55] One classification, which differs from that suggested by Tables VIII-1-1 and VIII-1-2, is as follows:[57]

- Natural polymer base.

- Synthetic base.
- Thermoplastics.
- Thermosets.
- Physical forms (one or more multiple components, films, etc.).
- Functional types (structural, hot melt, pressure sensitive, water base, UV cured EB cured, etc.).
- Chemical families (epoxy, silicone, phenolics, urethanes, polysulfides, etc.).

**Table VIII-1-1. Benefits and Limitations of Various Adhesive Types.**[58]

| Type | Anaerobics | Cyano-acrylates | Epoxies | Hot Melts | Light Cure | Silicones | Urethanes | Two-part acrylics[e] |
|---|---|---|---|---|---|---|---|---|
| **Performance considerations** | | | | | | | | |
| **Benefits** | High strength | Excellent adhesion to most rubbers and plastics | Wide range of formulations | Fast, large-gap filling | Rapid cure and adhesion to plastic | Excellent temperature resistance | Excellent toughness and adhesion | Good impact resistance and ductility |
| **Limitations** | Metals only | Low solvent resistance | Mixing required | Low heat resistance | Light-cure system required | Low strength | Sensitive to moisture | Mixing required |
| **Temperature resistance** | | | | | | | | |
| **Typical temp. $^{O}$C,** | -54 to 149 | -54 to 88 | -54 to 82 | -54 to 121 | -54 to 149 | -54 to 204 | -54 to 121 | -54 to 121 |
| **Highest rated temp., $^{O}$C** | 450 | 121 | 204 | 165 | 177 | 316 | 165 | 204 |
| **Environmental resistance** | | | | | | | | |
| **Polar solvents[a]** | Very good | Poor[d] | Very good | Good | Good | Good | Good | Good |
| **Nonpolar solvents[b]** | | Good | Excellent | Good | Very good | Poor to fair | Good | Very good |
| **Adhesion to substrates** | | | | | | | | |
| **Metals** | Very good | Very good | Excellent | Good | Good | Good | Good | Excellent |
| **Plastics [c]** | Fair | Excellent | Fair | Very good | Excellent | Fair | Very good | Excellent |
| **Glass** | Excellent | Poor | Excellent | Good | Excellent | Very good | Good | Good |
| **Rubber** | Poor | Very good | Fair | Fair | Fair | Good | Good | Poor |
| **Wood** | Good | Good | Very good | Excellent | Poor | Fair | Fair | Good |

[a]Water, ethylene glycol, UPA, acetone. [b]Motor oil, toluene, gasoline, ATF. [c]Uncured liquid adhesives may cause stress cracking of certain thermoplastics, e. g., polycarbonate, acrylic, polysulfon, (special products and process techniques are available). [d]Cyanoacrylates have very good moistures resistance on plastics. [e]Two-step-acrylic formulations are available for fast-process speeds or high-temperature-performance requirements.

By the addition of certain additives and/or by a change in formulation, adhesives may serve other functions: electrical and/or thermal insulation, electrical and/or thermal conductivity, prevent electrochemical corrosion at the joints between dissimilar metals, vibration damping, and provide smooth surfaces and smooth contours (important for aerodynamic efficiency). These functions would generally be unattainable using mechanical fasteners. Modifying the adhesive to obtain some of these objectives would usually also produce other changes in the properties of the joint, such as in mechanical properties and in peel resistance.

**Table VIII-1-2. Classification of Structural Adhesives.**[55]

| **Chemical types** | **Cure temp., $^{O}$C** | **Service temp., $^{O}$C** | **Lap shear strength, MPa at $^{O}$C** | **Peel strength, at RT, g/mm** |
|---|---|---|---|---|
| Epoxy formulated for room-temp. cure | 16 to 32 | —37 to 82 | 17.2 at RT<br>10.3 at 82 | 89.4 |
| Epoxy formulated for elevated-temp. cure | 93 to 177 | —37 to 82 | 17.2 at RT<br>10.3 at 177 | 89.4 |
| Epoxy-nylon | 121 to 177 | —253 to 82 | 41.4 at RT<br>13.8 at 82 | 1340 |
| Epoxy-phenolic | 121 to 177 | —253 to 260 | 17.2 at RT<br>10.3 at 260 | 179 |
| Butyral-phenolic | 135 to 177 | —37 to 82 | 17.2 at RT<br>6.9 at 82 | 179 |
| Neoprene-phenolic | 135 to 177 | —37 to 82 | 13.8 at RT<br>6.9 at 82 | 268 |
| Nitrile-phenolic | 135 to 177 | —37 to 121 | 27.6 at RT<br>13,8 at 121 | 1072 |
| Urethane | 24 to 121 | —253 to 82 | 17.2 at RT<br>6.9 at 82 | 894 |
| Polyimide | 288 to 343 | —253 to 538 | 17.2 at RT<br>6.9at 538 | 53.6 |

Although sealants are generally not discussed in this report, it should be pointed out that sealants have many of the same characteristics as adhesives: their molecular structures, storage limitations, surface preparations, curing, etc. An exception would be that an adhesive in a structural component would have a higher performance level than the corresponding sealant. Some adhesives serve equally well as sealants, especially where both bonding and sealing are required together.

## VIII-2. Some Structural-Adhesive Types [59]

Only a very brief explanation/definition of some of the structural types of adhesives will be presented in this section. A summary of the principal characteristics is listed in Table VIII-2-1.

Epoxy adhesives are the reaction products of acetone and phenol. They are the most popular of all structural adhesives. Epoxies (epoxide adhesives) are thermosetting polymer resins, which cure either by heating (in one-part systems) or by addition of a hardener or catalyst (in a two-part system) or by both with little or no need of pressure, becoming rigid through the formation of dense cross-linking. The reaction is exothermic and care must be taken to avoid overheating causing the formation of voids. In addition to hardeners and catalysts, other additives may be used to modify the properties of the epoxy. The highest strengths (up to 77.2 MPa) are obtained with the heat-cured two-part epoxies. As a group, epoxies have low shrinkage, they tend to have low flexibility with poor impact strength, and they have low peel strength. Like most thermosetting polymers, they have good resistance to solvents.

The brittle behavior of the cured thermosetting-polymer resins is overcome by incorporating various thermoplastics or elastomers that impart flexibility and toughness to the epoxy. The peel strength is also improved. These epoxies are known as modified epoxies; some examples are epoxy nylon, epoxy-polysulfide, epoxy-phenolic, and epoxy-nitrile (rubber).

**Table VIII-2-1 Summary of Principal Characteristics of Major Structural Adhesives.**[59]

| Adhesive | Type | Cure | Shear Strength, MPa | Peel Strength, N/m | Impact Resistance | Solvent Resistance | Moisture Resistance | Substrates Bonded |
|---|---|---|---|---|---|---|---|---|
| Epoxies | One-[a]<br>Two-<br>F&T[b] | Heat<br>RT/heat<br>H + P[c] | 15.4 | <525 | Poor | Excellent | Excellent | Most |
| Polyure-thanes | One-<br>One-<br>Two- | Heat<br>Moisture<br>RT/heat | 15.4 | 14,000 | Excellent | Good | Fair | Most. Smooth & nonporous |
| Modified Acrylics | One- | RT/heat | 25.9 | 5,250 | Good | Good | Good | Most. Smooth & nonporous |
| Cyano-acrylates | One- | Moisture | 18.9 | <525 | Poor | Good | Poor | Nonporous, metals & plastics |
| Anaero-bics | One- | No oxygen | 17.5 | 1,750 | Fair | Excellent | Good | Metals, glass & thermosets |
| Silicones | One- | Moisture | 1.7-3.4 | 612 | Good | Good | Excellent | Most |
| Phenolics | One-<br>Two-<br>F&P | Heat<br>Heat<br>H + P | N/A | N/A | Fair | Good | Good | Most |
| High-Temp | One-<br>F&P | Heat<br>H + P | 8-14 | N/A | Fair | Fair | Poor | Thermo-plastics & metals |
| Hot-melts | One- | Heat | 4.3 | N/A | Eair | Fair | Good | Thermo-plastics & metals |

[a]Numbers indicate number of components. [b]F&T indicates film and tape. [c]H + P indicates heat + pressure.

Acrylic adhesives are based on acrylic monomers of ethyl acrylate, methyl acrylate, methacrylic acid, acrylic acid, acrylamide, and acrylonitrile. They are all two-part systems. They are not mixed for application; rather, the resin is applied to one adherent, and the accelerant applied to the other adherent. When mated, the bonding reaction occurs quickly (in minutes) even at room temperature. Pretreated parts can be stored separately for some time before bonding. Shear strengths can reach 28 MPa. Acrylics have been developed known as modified acrylics, in which the bonding has been significantly enhanced by the addition of certain additives. They offer good peel, impact, and tensile-lap strengths over the temperature range of –110 to $120^{O}$C. The modified acrylics, however, are quite flammable.

Examples of modified acrylics include acrylic-latex, acrylated silicones, acrylated urethanes, and acrylated silicone-urethanes. Silicone additions improve thermal stability, tensile strength, and resistance to solvents, abrasion, and ultraviolet light. Urethane additions increase toughness, thermal stability, and resistance to solvents, abrasion, and ultraviolet light.

Cyanoacrylates (“super glues”) are composed of low-viscosity, liquid-acrylic monomers, which polymerize easily in the presence of adsorbed water, especially if the adherent surface is slightly alkaline. Strong thermosetting bonds can be created with many materials with no added heat or catalyst since most materials have absorbed water present. Shear strengths up to 38.6 MPa are attainable; peel strength and impact resistance are low and tolerance to moisture is poor. The principle advantage to cyanoacrylates is that they bond in seconds – they will bond to almost any substrate. Methyl cyanoacrylate produces stronger and more impact-resistant joints than ethyl cyanoacrylate when bonding rigid materials. The latter, however, produces stronger and more durable joints with elastomeric, thermosetting, or thermoplastic polymer adhesives. The peel strength of cyanoacrylates is poor and tend to be brittle, with limited temperature resistance.

Anaerobic adhesives and (more properly) sealants are single-component monomeric liquids that only harden satisfactorily in the absence of oxygen (air). They must be stored in the presence of oxygen. They have high fluidity and readily flow into small crevices, and cure with little or no shrinkage providing thorough sealing. Addition of some urethane overcomes brittleness and improves peel and impact strengths.

Urethanes, or polyurethanes, are basically thermoplastic polymers that have the ability to develop cross-links under certain conditions, thereby making them fairly rigid thermosetting adhesives. They are available in one- and two-part systems They have inherently better flexibility and higher peel strengths than do the epoxies. They are generally applied to both adherents and are brought together when the proper tackiness is reached. Curing, which is usually done at room temperature, should be initiated immediately and may take hours or days. Heat can soften the adhesive if it becomes too dry before bonding.

Silicones are one- or two-component systems that cure to thermosetting solids. One-component systems cure at room temperature when exposed to atmospheric moisture. Two-component systems that cure by condensation polymerization are prone to polymerization reversion or decomposition. Silicones have good peel strength over the temperature range of –60 to 250$^{O}$C, and some survive limited exposure up to 370 $^{O}$C. Flexibility, impact resistance, and resistance to moisture, hot water, oxidation, and weathering are very good. Lap-shear strengths tend to be low. They are relatively expensive. They are versatile and are bondable to almost any material.

Phenolic or (more properly) phenolic-formaldehyde adhesives rely on penetration of the pore or cell structure (e. g., wood) of the adherent to develop bonding forces. They can be used as a primer on metals. They are frequently combined with other polymers to produce adhesives having one or more enhanced properties: higher bond strength, higher fatigue strength, higher service temperature, and better resistance to water, humidity, salt, or/and weather. For example, epoxy-phenolics offer excellent long-term service between 150 and 260$^{O}$C, and down to –260$^{O}$C if specially formulated.

High-temperature structural adhesives are largely based on synthetic organics that have open-ring structures that close upon exposure to heat. Thus, instead of softening or decomposing, they become stronger on heating. Two specific high-temperature structural adhesives are the polyimides and the polybenzimidazoles. These are both expensive and difficult to handle in that they have long cure times and emit considerable volatiles. Polyimides offer superior long-term-strength retention in air up to 260$^{O}$C, while polybenzimidazoles are stable up to 288 $^{O}$C, but only for short times. Both are prone to degradation by moisture. Their principle use has been in aerospace structures for metal-to-metal or metal-to-composite bonds.

Hot-melt adhesives are copolymers of polyethylene with polyvinyl, polyolefins, polyamides, polypropylene, nylon, polyester, and thermoplastic elastomers. They are 100% thermoplastic, i.e., they will soften on heating and harden on cooling. They generally tend to soften at temperatures between about 80 and 100$^{O}$C. Some types will soften at temperatures of over about 100$^{O}$C. They are applied in the molten state at temperatures mostly between about 150$^{O}$C and 400$^{O}$C depending on the adhesive. Most hot-melts contain a diluent and/or filler. They can be formulated to make either flexible or rigid bonds and they will reach 80% of their bond strength in seconds after application. They can bond to either permeable or impermeable surfaces They are quite resistant to moisture. There are high-performance hot-melts, such as polyamides and polyesters that can produce bonds to withstand limited loads at elevated temperature without undergoing significant creep.

## VIII-3. Storage Life and Exposure of Adhesives

Adhesive and sealant materials have finite lives in storage. After being compounded, their useful lives are further limited. Shelf life can vary from a few days to about a year depending on the components used in the mixture and handling. Generally the two-component products have much longer shelf lives than the one-component ones. The shelf life depends also on storage temperature, which can be as low as –18°C, allowing storage of most materials to between six months and a year.[60] Two-part systems, such as epoxy adhesives that contain a catalyst and resin, when premixed are stored at temperatures below -40 °C until used. The premixing is done under vacuum to avoid moisture/air entrapment. Quick-setting epoxies should generally be avoided. Because of their limited pot life, bonding operations must be completed within an hour.[61]

Some materials cannot tolerate subzero temperatures; for example, freezing can damage the emulsions of aqueous solutions and dispersions. As some of the components may react exothermically (heat evolution), it is important not to store them above their specified maximum storage temperature. After mixing, an exothermic reaction may provide sufficient heat for curing or even cause overaging. The stored materials may also be adversely affected by light and humidity. Some materials must be stored in the dark or in opaque containers.[59] Resins and curing agents for thermosetting adhesives should be stored apart to prevent accidental contamination should container breakage or leakage occur. Exposure of a sealant in an uncovered container just for a day may result in the adsorption of excessive moisture. Unsealing a container too soon after removal from cold storage may cause excessive condensation. If the stored product deteriorates, the curing behavior, which depends on the characteristics of the product (e. g., a viscosity increase of liquid or paste, or lack of tack of films, etc.), is affected resulting in a degraded adhesive bond. An example of a loss in strength due to aging of an epoxy-film adhesive is shown in FigureVIII-3-1.[60] The change in viscosity as a function of time for a paste adhesive is shown in Figure VIII-3-2. The increase in viscosity is initiated just before the expired shelf life.[60]

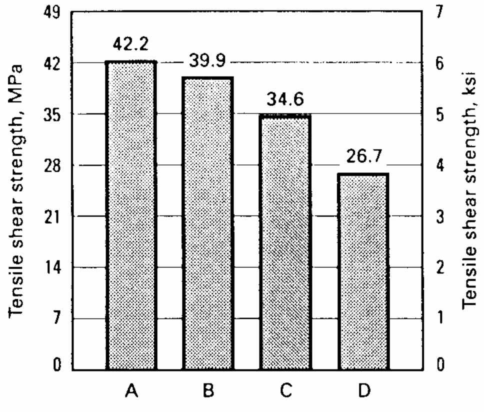


Figure VIII-3-1 Effect of aging conditions on an epoxy-film adhesive: A—fresh adhesive; B—cured after 90 days at 24°C; C—cured after 90 days at 32 °C; D—cured after 1 hour at 50 °C in a 95-to-100% humidity chamber. (Normal120 °C-cure cycle used after aging)[60]

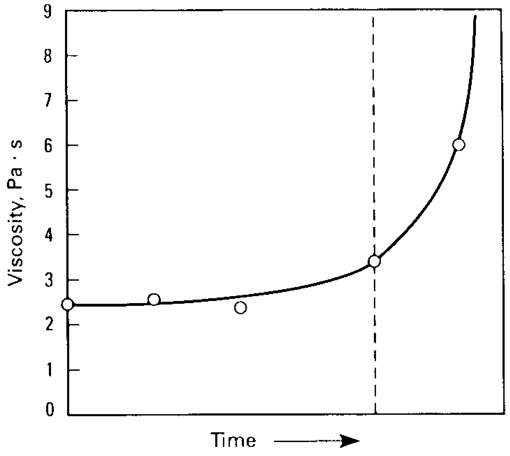


Figure VIII-3-2. Change in viscosity of a paste adhesive as a function of time at room temperature. Shelf life is indicated by vertical dashed line.[60]

## VIII-4. Surface Preparation

Adhesive-joint failure can be due to a number of factors such as poor design, improper adhesive selection for either one or both of the substrates, the operating environment (especially temperature), service overload or inadequate bond strength, and/or inadequate surface preparation.[58] Surface preparation is claimed to be by far the most important factor in producing a good adhesive bond.[9, 61] The main steps are degreasing, acid cleaning, neutralizing, drying, applying the adhesive, and subjecting the joint to the recommended heat and pressure. An appropriate fixture would be used to restrain the joint during curing. If service temperatures are between –50 and 120°C, it is best to select an adhesive curable at room temperature.[61] Because of the great importance given to surface preparation, a number of examples of surface preparation will be given. A handbook on adhesives lists a number of methods that have been investigated and are said to appear promising.[62] These are listed in the following, all adherents (substrates) had first been vapor degreased:

**Method A.**[p]

1. Immerse (adherent) for 3 to 4 min. in a solution of 20% wt. of sodium hydroxide in distilled water maintained at 77 to 82°C.
2. Rinse with cold water
3. Oven dry at 135 to 149 °C for approximately 15 min. Bond or prime as soon as possible.

**Method B.**

1. Immerse for 8 to 10 min. in a solution of 283 grams of Prebond 200 (American Cyanamid Company) to 3.8 liters (one gallon) of water.
2. Rinse thoroughly.
3. Oven dry at 79 to 93°C for 15 min.

---

[p] Method suggested also by L. P. Althouse at LLNL in UCID 16997, Feb. 2, 1976. Degreasing was done by wiping with trichloroethylene.

**Method C.**

1. Immerse for 8 to 10 min. in method B.
2. Rinse.
3. Immerse for 10 min. in a 20% chromic-acid solution maintained at 82 to 93$^{O}$C.
4. Water-rinse at 54 to 60$^{O}$C.
5. Force dry at 82 to 93$^{O}$C for 30 min.

**Method D.**

1. Liquid hose using Burr-al, 220 grit.
2. Alkaline clean (use Method B).

**Method E.**

1. Degrease with MEK followed with a vapor degrease.
2. Etch for 30 sec. in a solution of 45 nitric acid-7 hydrofluoric acid-260 distilled water (parts by weight) maintained at 21 to 27$^{O}$C.
3. Rinse thoroughly.
4. Dry for 20 to 30 min. at 71 to 82$^{O}$C.

**Method F.**

1. Immerse for three min. in a solution of 420 hydrochloric acid-44 phosphoric acid-32 hydrofluoric acid (parts by weight) maintained at 21 to 27$^{O}$C.
2. Remove smut (if any) with MEK.
3. Rinse thoroughly.
4. Dry at 82 to 88$^{O}$C.

**Method G.**

1. Apply the following paste to the faying surface for three min. at room temperature: 10 sulfuric acid-1 sodium dichromate-30 water (parts by weight). Add Cab-o-Sil (Cabot Corp.) to make a thixotropic paste, or it may be used as a hot solution maintained at 66 to 71$^{O}$C.
2. Rinse.
3. Dry thoroughly.

The tensile-shear strengths of beryllium-beryllium bonds utilizing various adhesives following the surface-preparation of Method G and tested at a series of temperatures are shown in FigureVIII-4-1. The tensile-shear strengths of the beryllium bonds utilizing epoxy-phenolic and four different surface-preparation methods are shown in Figure VIII-4-2.

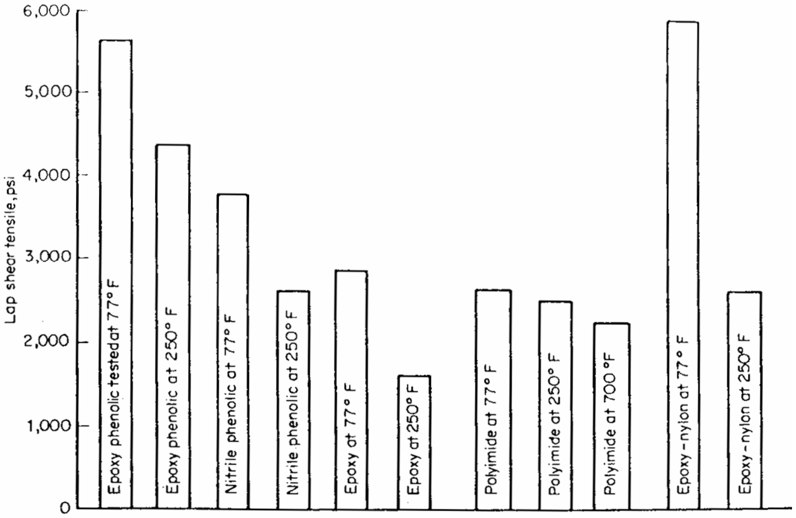


Figure VIII-4-1. Tensile-shear strengths obtained at a series of temperatures for beryllium-beryllium bonds utilizing various adhesives and a sulfuric acid-sodium dichromate paste (Method G). Test temperatures are shown.[62]

Surface-preparation steps for beryllium that have also been given are:[53] degrease with trichloroethylene, immerse for five to ten minutes in a sodium-hydroxide solution (one part NaOH to 6 to 8.5 parts distilled $H_2O$, by weight), wash in tap water, rinse in distilled water, and finally oven dry for ten minutes at 122 to 177$^{O}$C.

Another method reported for surface preparation was to coat the beryllium surface with an epoxy-based-paint primer within eight hours following etching.[61] Etching was used to remove the machining-damaged surface. This provides protection from corrosion and significant storage time prior to bonding. The etch process provides a matte finish that results in good adhesion bonding. A strippable primer can also be used to protect the surface. All that will be required prior to bonding is a thorough wipe with either MEK or acetone. If a primer is not used, the surface should be thoroughly scrubbed with a cleansing powder free from halogens until a water-break-free surface is obtained. The part should then be etched to remove 3 to 5 μm of surface metal, rinsed, oven dried, and bonded within two hours. Scrubbing and rinsing should be done with deionized water to avoid any corrosive attack. A slightly acidic water is suggested to avoid corrosion problems.[61] Surface abrasion may add to the bond strength by facilitating mechanical interlocking. Surface abrasion would generally be limited to relatively inactive materials such as stainless steel.

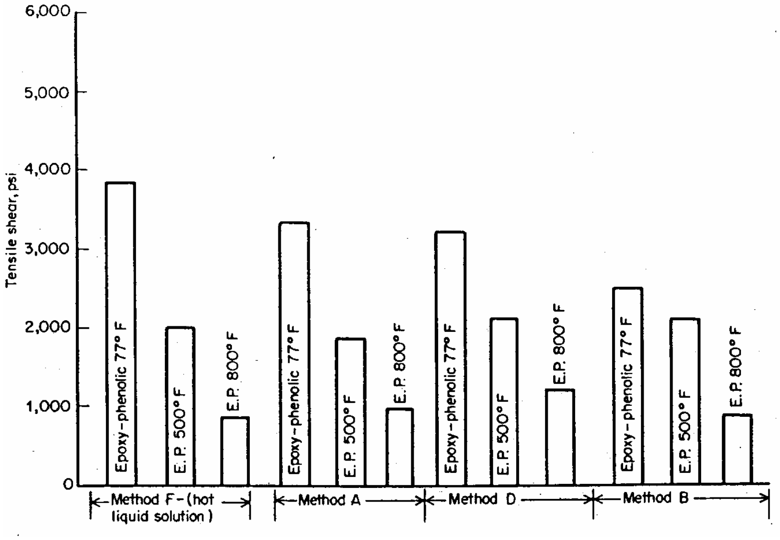


Figure VIII-4-2. Tensile-shear strengths obtained at a series of temperatures for beryllium-beryllium bonds utilizing an epoxy-phenolic adhesive and four different surface-preparation methods (see text). Test temperatures are shown.[62]

An evaluation of etchants used in a surface-preparation procedure for beryllium was reported using the following procedure:[63] degrease in a proprietary solution of P3 VR580-4 (buffered alkaline solution) at 80$^{O}$C for 20 minutes; rinse in running water; etch; rinse in running water; final rinse in deionized water; dry in an oven at 70 $^{O}$C; apply primer; cure primer; and store in sealed polyethylene bags. Four different etchants were evaluated based on control of the etching reaction, having a free-water-break surface (no interference of flow of rinsing water), surface appearance, and the relative shear-strength values obtained with single-lap bond tests. The etchant-reactions and surface appearances obtained for the different etchants are:

Etching at room temperature with potassium dichromate plus sulfuric acid gave extremely vigorous reaction and rapid metal removal; developed rough surface; etch for 2 to 3 min. using dilute concentrations (90 g $K_2Cr_2O_7$ + 200 ml $H_2SO_4$ + 3800 ml $H_2O$). Use only with cooling or in large baths.

Etching 5 min. at 90 $^{O}$C with sodium hydroxide (20%) gave controllable reaction with minimal metal removal; developed an evenly matte surface; loose surface deposit formed that was easily removed on rinsing.

Etching 8 min. at 90 $^{O}$C with Prebond 700 gave controllable reaction with minimal metal removal; developed a clean, evenly matte surface; least problematic of the four treatments. All four treatments exhibited good water-break-free characteristics. Treatment 4 was selected as the most suitable for the subsequent studies.

Nitric acid (28%) + hydrofluoric acid (2%) + $H_2O$ 70) gave a somewhat vigorous exothermic reaction; developed an evenly matte surface, although rougher than with treatment 2 or 3 and less rough than with treatment 1.

Prior to etching, all parts (sheets) were degreased at $80^{O}C$ for 20 min. using a proprietary buffered alkaline solution (P-3VR580-4), rinsed in running water, and then etched using the above procedures. The parts were then again rinsed in running water, followed by a final rinse in deionized water and then oven dried at $70^{O}C$. The parts were then primed and stored in sealed polythene bags until bonded.

All four treatments exhibited good free-water-break surfaces. Procedures 2 and 3 produced the best shear-strength values of 35.5 and 36.7 MPa (average of seven tests each), respectively. The adhesive system FM 1000/Br 1009-8 was used with curing in an autoclave. Values of 45.4 and 48.5 MPa (average of seven tests each), respectively were obtained using the adhesive system FM 123-5/BR 127. Additional tensile, sheer, and fatigue tests were performed evaluating different adhesive systems and comparing adhesive bonding with riveting and with the combination of rivets and adhesives. Adhesive bonding proved to be best.[63]

## VIII-5. Applying Adhesives

Adhesives may be applied either as a liquid, paste, film or tape. The transportation industries are the largest users of adhesives, with the aerospace industry featuring the most critical applications.[60] For structural components, the aerospace industry commonly uses a one-component, film-type adhesive, which is applied to chemically prepared substrates under environmentally controlled conditions. The resultant assembly would then be cured in a heated autoclave under controlled temperature and pressure conditions. The use of liquid or paste adhesives in the transportation industries is largely confined to secondary bonding, repair, or rework activities. The liquid must be able to wet the adherent, and in some cases change its state or react with it. This is most obvious with organic adherents.

Various methods are described for applying liquid adhesives:[53]

- Brushing: uneven films likely, for selected areas or complicated shapes, use stiff brush.
- Flowing: for flat surfaces, fast assembly if use pressure-fed flow guns, better thickness control than with brushing.
- Roll coating: for wide sheet and film, material is coated with adhesive as material passes between transfer roller(for adhesive) and pressure roller (controls adhesive thickness), best method for speed and uniformity.
- Knife coating: adjustable knife-blade, rod, or bar controls both the adhesive flowing onto a moving sheet and the adhesive thickness.
- Silk screening: for bonding selective areas or patterns.
- Melting: hot-melt-type adhesive is heated to a fluid state and dispensed by suitable nozzles to the workpiece, can be applied to knife-coating techniques.

Flowabilty is one of the most important properties of an adhesive. Too little flow produces patchy, void-containing bonds with low strength areas. Excess flow results in variable bond-line thickness and unreproducible strengths in metal-to-metal bond joints.[53]

## VIII-6. Curing Adhesives

Curing variables (temperature, time, mechanical restraint, and applied pressure) will depend primarily on the type of adhesive.[53] A number of heating methods can be used: ovens, hot presses(or platens), liquid bath such as silicone oil (but avoid contact with bond), infra-red radiation, metal or graphite conductor strip embedded in adhesive, wrap-around heating tapes, heat from ultrasonic activation energy at the bond interfaces, and induction heating. Using graphite-conductor strips produced bond strengths comparable to strengths obtained by oven curing and offers a number of advantages: easy access of heat to localized regions, uniformity of strips avoids hot or cold spots, less distortion, rapid heating, close control of bond-line temperature, avoids heating complete assembly, and reduces processing time.[53] A constant pressure should be sustained to allow for dimensional changes during curing, such as shrinkage. Some adhesives contain volatile components to improve their consistency, and provisions should be made for their removal as well as for the possibility of by-products being formed during curing.

To avoid squeeze-out during clamping and curing, spacing beads (0.05 to 0.15 mm dia.), which are usually made out of ceramic, can be used to keep the mating parts from touching. The beads, which would amount to only about 0.5% of the adhesive weight, should not affect the bond strength.[61] To assure a uniform thickness when applying a wet adhesive, the adhesive can be spread with a comb-like tool. To minimize run-out after assembly, it is best to have the adhesive slightly gel before assembling the mating surfaces. When assembling the parts, sliding or swiping movements must be avoided to prevent introducing bubbles into the adhesive. For room-temperature curing systems, a 16-hour period is the minimum time for keeping the parts in a restrained position before handling; maximum loads should not be applied until after seven additional days when full strength should be reached.[61] Epoxies can frequently be cured by holding at 90$^{O}$C for one hour, still following the 16-hr. restrained-position period. The times and temperatures should be verified for each adhesive system. If a bond is found to be defective and not repairable, the joint can be disassembled by heating the part to 350$^{O}$C for one hour, which will crystallize most adhesives, facilitating the separation of the mating surfaces. The beryllium should not be affected by the heating. Surfaces must be properly prepared, as before, for rebonding.[61]

## VIII-7. Some Reported Results on Mechanical Properties

The effect of operating temperature on the tensile strength of a beryllium joint bonded with a polyimide adhesive is shown in Figure VIII-7-1.[55] Surface preparation of machined beryllium (S-200D) test samples used for evaluating adhesive bonding of beryllium hemispheres was reported as follows:[64]

- Stress relief at 800 $^{O}$C for one hour in a high vacuum (better than $10^{-6}$ torr) followed by very slow cooling (approx. 1 $^{O}$C/min.).
- Vapor degrease in trichloroethylene.
- Immerse in Mitchel-Bradford MI-20 detergent cleaner for 15 min. at 60 $^{O}$C.
- Rinse in demineralized water.
- Dry in vacuum oven at 560 mm of mercury at 50 $^{O}$C.

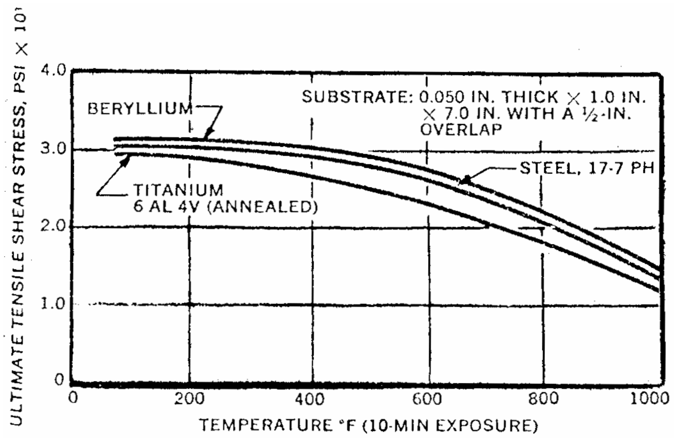


Figure VIII-7-1. Effect of operating temperature on the tensile strength of beryllium, steel, and titanium bonded with polyimide adhesives.[55]

The epoxy adhesive (Dexter-Hysol EA9330) used following the above surface preparation was prepared as follows:

1. Mix a small quantity of adhesive vigorously for five min. using 33 parts B to 100 parts A.
2. Degas in vacuum at 560 mm of mercury for five min.
3. Apply adhesive to the substrates as quickly as possible.
4. Cure samples under a pressure of approximately 97 kPa applied by weight or spring at 23$^{O}$C for 16 hours followed by 82$^{O}$C for two hours.

Using the latter procedures, butt-adhesive-bonded tensile samples gave fracture strengths of 60.5 ± 3.4 MPa at room temperature, which increased to about 131 MPa at -269 $^{O}$C. Pressurized burst tests on adhesive-bonded-beryllium hemispheres gave burst strengths of about 24 and 172 MPa, without any prior stress relief and following a stress-relief treatment, respectively. It was proposed that the thin oxide layer formed during the stress-relief treatment (in spite of the high vacuum) was better suited chemically for the adhesive bonding than was a metallic beryllium surface.

Adhesives applied to beryllium in the manufacture of the space-shuttle-orbiter navigation base are listed in Table VIII-7-2.[43] Bonding was performed on 36 detail parts in six different stages using five different adhesives. All the beryllium details were etched and primed with BR127 primer. The effect of using different adhesive systems on the strength of beryllium joints can be seen in Table VIII-7-3.[9] Two adhesives that have been successfully applied to beryllium in space-hardware applications are EA934 (Hysol Corporation) and Epon 825 (Shell Chemical). Two adhesive systems that were successfully used in an evaluation investigation on bonding beryllium are FM 1000, an unsupported polyamide epoxy film adhesive with a curing temperature of 175$^{O}$C, and FM 123-5, a supported nitrile epoxy film adhesive with a curing temperature of 125$^{O}$C. Both adhesives were used with compatible primer systems, FM1000/BR 1009-8 and FM 123-5/BR 127, respectively.[63] (Adhesives and primers were obtained from Bloomingdale Division of American Cyanamid Company.)

**Table VIII-7-2. Adhesives Used in Multistage Bonding of Space-Shuttle Orbiter.**[43]

| Adhesive | Type of Joint | Cure temp., °C | Cure time | Pressure, kPa |
|---|---|---|---|---|
| Epoxy-phenolic HT424 | Be splices to Be fitting | 171 ± 5.6 | 60 to 90 min. | 69 (min) |
| Nitrile epoxy FM 123 & FM 37 | Be honeycomb panel | 121 ± 5.6 | 60 to 90 min. | 310 |
| FM123 | Be splices to Be panel | 88 ± 5.6 | 6 to 7 hours | 69 to 103 |
| Epoxy No. 206 | Be splice to edge panel | Room temp.<br>or 82 ± 5.6 | 72 hours<br>1 to 2 hours | 69 to 103<br>69 to 103 |
| EA 934 | Small tool holes and gaps | Room temp.<br>or 46 to 82 | 24 hours<br>6 hours | Contact<br>Contac |
| Epoxy No. 206 | Titanium and CRES fittings to Be upper surface | Room temp.<br>or 82 ± 5.6 | 72 hours<br>1 to 2 hours | 69 to 103<br>69 to 103 |

**Table VIII-7-3. The Influence of Adhesive System on the Strength of Adhesive-Bonded-Beryllium Joints**.[9]

| **Adhesive System** | **Average Strength** | **Type of Test** |
|---|---|---|
| EA-9309-BR127 Primer | 32.4 MPa | Lap shear |
| HT-424-BR127 Primer | 17.2 MPa | Lap shear |
| FM-123-BR127 Primer | 24.1 MPa | Lap shear |
| FM-123-BR127 Primer | 985 kg/m | Honeycomb peel |
| EA-934-BR127 Primer | 75 Shore D | Hardness |
| Epoxy Np. 206-Grade A | 24.1 MPa | Lap shear |
| BR127 Primer | 716 kg/m | 90-degree peel |

In a study on the strength of beryllium/stainless-steel adhesive bonds, various adhesives and several types of beryllium were evaluated.[65] The stainless steel consisted of two threaded grips with flat faces between which either a disk or square beryllium sample 2 to 3 mm thick was bonded to the steel. The samples, which were oversized to prevent edge effects, were grit blasted, degreased, and bonded within 24 hours. After 14 days storage at room temperature, they were tested in tension (1.27 mm/min. crosshead speed) The adhesives used were:

- Epoxide—Epikote 828-100 pbw Resin and Versamid 125-100 pbw Polyamide,
- Polyimide—Keramid 500-(Rhone-Poulenc Paris),
- Urethane—CS 8097-two part polyurethanes and Bostik Quickset, and
- Cyanoacrylate—IS 150 (thickened version) Loctite.

A polyamide-curing system was used for the epoxide to avoid the possible corrosive effect of amine hardeners on beryllium. The beryllium samples were:

- fully-dense CIP-HIP P-1-grade (electrolytically refined) beryllium,
- 95%-dense hot-pressed P-10-grade (commercial-purity) beryllium, and
- 90% dense, plasma–sprayed-and-sintered (PSS) P-10-grade beryllium.

The urethane and epoxide adhesives were found to have marginally superior strengths, roughly of the order of 30 to 40 MPa with the epoxide giving the most consistent higher strengths for all beryllium grades. Poor tensile results were obtained for the PSS P10 beryllium when bonded with cyanoacrylate. This was attributed to the high porosity of the PSS beryllium and the poor gap-filling properties of this class of adhesive. Preliminary aging studies with Epoxide and Urethane for up to six months at $60^{O}C$ indicated that significant strength increases are attainable by aging.

## IX. Mechanical Fasteners (Joining)

Mechanical fasteners for beryllium generally fall into two categories, namely, bolts and rivets. In both categories, a hole must first be created in the metal. Producing holes that are free from cracks and delamination is considerably more difficult with beryllium than with other metals.[61] A more complete list of mechanical fasteners and other mechanical fastening methods, many of which may not normally be applicable to beryllium, and are described in considerable detail in the reference, include the following: fasteners such as bolts, screws, rivets, dowels, pins, nails, keys, retaining rings, eyelets and grommets, stapling, stitching, snap fits, and clips; integral design features such as flanges, interlocking members (tongue-and-groove, teeth, and tabs), roughened gripping surfaces, and deformed features (crimps, hems, punch marks, and stakes).[66]

In a mechanically fastened assembly, the load is transferred between components through the fasteners such that high stress concentrations are developed at the fasteners and surrounding metal. With poor designs, these high stresses can lead to premature failure. In addition, the stress concentrations can lead to distortion of the fastener hole and/or the fastener, especially in a component that exhibits viscoelastic behavior. Some of the loading may be carried by friction between the joined members. Simple examples of mechanical fastener joints are shown in Figures IX-1 and IX-2, the latter figure illustrating some stress patterns. As in the case with adhesive joints, differences in the coefficient of thermal expansion between the beryllium and the fastener as well as between the beryllium and mating component should be considered with reference to the service-temperature range.

Some advantages of mechanical fasteners over adhesive bonding are:[66]

- Allows disassembly, with little or no destruction of components.
- Can permit relative motion.
- Causes no change in chemical composition or microstructure.
- Dissimilar types of material can be joined.
- Allows for damage tolerance to assembly.
- Does not require any special joint preparation.
- Relatively low cost (unless large installation costs occur).
- More adaptable to being automated.

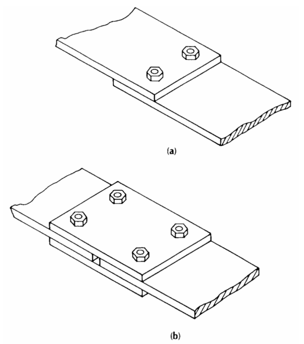


Figure IX-1. Illustrations of two mechanical-fastener, shear-loaded joints: (a) lap-joint, (b) butt-type (or double–lap) joint.[66]

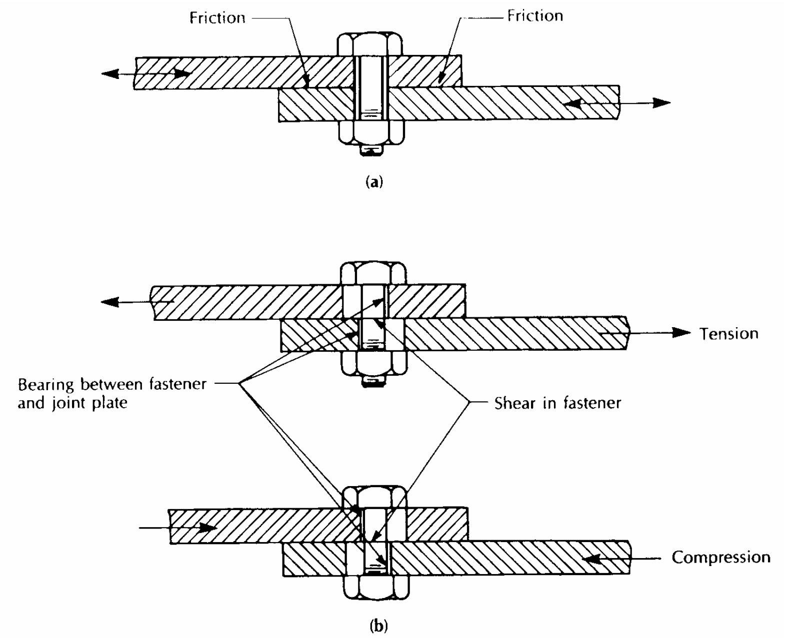


Figure IX-2. Illustrating differences between (a) friction-type joints and (b) bearing-type joints; in the latter case the load is transferred essentially through the fastener, thus introducing a shear stress across the fastener.[66]

Some of the disadvantages of mechanical fasteners over adhesive bonding are:[66]

- Creates significant stress concentrations.
- Allows fluid intrusion or leakage.
- Entrapment of corrosive agent, accelerating corrosion.
- May involve high labor-installation costs.
- Joints can loosen in service under vibration, flexing, thermal cycling, etc.
- Increased weight.
- Utility limited with some materials.
- Possible fastener pull-through or pull-out.
- In drilling holes in the beryllium component, a vacuum system must be used to collect the machining chips.

Holes in beryllium can be produced either by drilling or by electrical-discharge machining.[q] The advantages of EDM over drilling are that it offers the possibility of creating many holes simultaneously and shapes other than cylindrical can be made. Minimum radial clearance for bolts and rivets is given as 0.025 mm; the clearance must also allow for expansion of the rivet.[61] If holes have to be threaded, it is best to use a torque-controlled machine rather than hand threading. The drill tool must have a rounded-root configuration. It is suggested, when eliminating machining damage, that a stress relief is preferable to etching as the etching may alter the thread configuration. A recommended stress-relief schedule for a threaded hole is shown in Figure IX-3.[61]

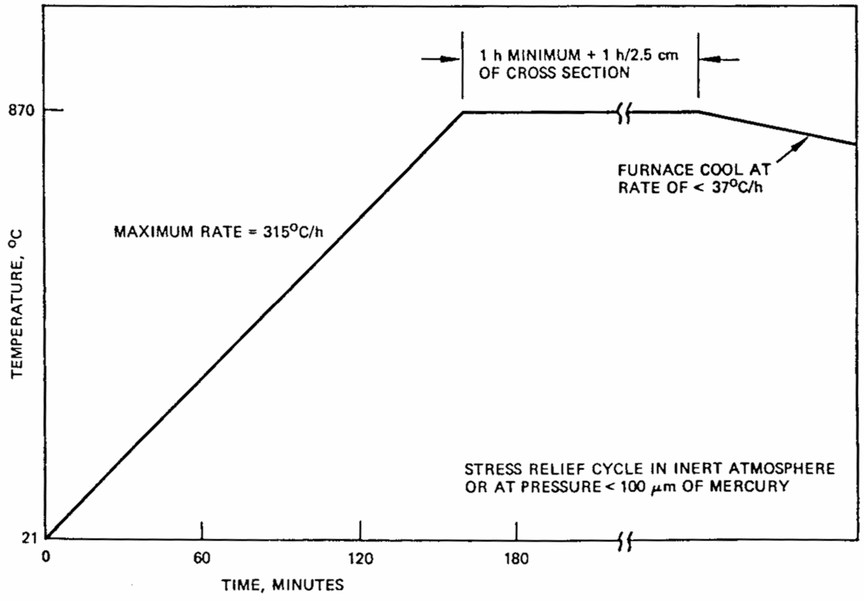


Figure IX-3. Stress-relief cycle for removing machining damage of a threaded hole following cycle used for beryllium hot-pressed block.[61]

Following a stress relief, the thread configuration, dimensions, and tolerances must conform to specifications (MIL-S-7742 was indicated in reference 61). Structural inserts can be used to prevent wear and damage (galling, stripping, corrosion) of the beryllium threads. A helical-coil-type insert is suggested as it does not require any staking into the part for retention and thus avoids any installation-impact forces on the beryllium.[61] Where nut plates are used (instead of tapping into the beryllium), it is best to bond the plates to the beryllium rather than attach them with rivets. Using nut plates will usually require fewer drilled holes in the beryllium as each nut could be loaded to higher stresses than would be accommodated in a threaded beryllium hole.

A bolt acts as a pin in preventing relative slipping between the joined components and as a heavy spring clamping the components together. It should be noted that the behavior and life of a mechanical joint would depend as much, if not more, on the correctness of the clamping force holding the components together than on any other design factor or environmental factor.[67] In general, the maximum clamp forces that the components can withstand should be used. In addition to the tensile stresses introduced by tightening of the nut, the frictional forces between nut and bolt threads introduce torsional forces, and bending stresses may develop due to any

---

[q] Drilling and EDM are discussed in Sections VII-3 and VII-8, respectively. Thread forming is discussed in Section VII-8.

misalignment of the bolts and nuts with component surfaces. The author visualizes this behavior as shown in Figure IX-4, where the interaction between components is represented by a heavy spring being compressed by a group of small springs (bolts).[67]

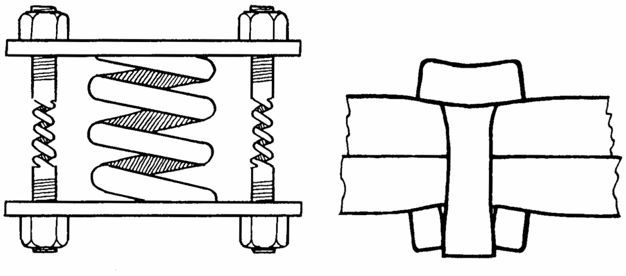


Figure IX-4. Illustration of distortions developed by clamping. Components represented by heavy spring during bolting being compressed by a group of small springs (bolts). Distortion of the solid spring (components) is shown greatly exaggerated on the right.[67]

Rivets are the most commonly used unthreaded fasteners for structural joints. A rivet consists of a head and a smaller diameter shank made from plastically deformable material (metal or thermoplastic). After inserting the rivet through the aligned holes of the components to be joined, the protruding portion of the shank is upset creating a second head. The principle is illustrated in Figure IX-5 for solid and tubular rivets. There are many types of rivets with a variety of head shapes used for different applications.[66] The solid shape shown in the figure is considered as the standard structural rivet and can be either hot or cold driven. The upsetting force depends on the material, size, and temperature of upsetting. The use of squeeze-type rivets are preferred for beryllium in contrast to those requiring an upset force.[66]

Although extensive information is available in the literature on mechanical fasteners, very little was found that pertained to beryllium. This suggests that the use of adhesive is largely preferred over the use of mechanical fasteners for joining of beryllium. Probably, the largest use for beryllium has been in aerospace and transportation applications and here the weight factor is an important criterion in selecting the manufacturing methods to be used.

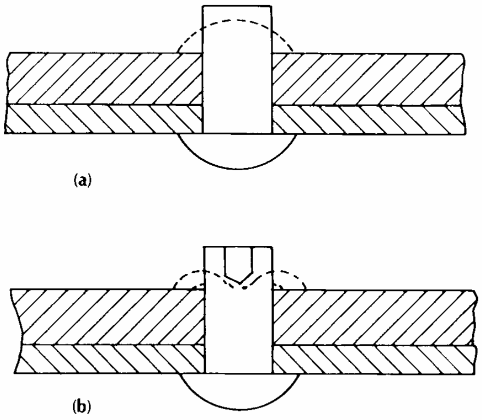


Figure IX-5. Solid (a) and tube (b) rivets in a joint, before and after upsetting. Solid line—before upsetting; dashed line—after upsetting.[66]

## References

1. J.M. Marder, etal., Near Net Shape Beryllium Products, The International Journal of Powder Metallurgy, vol. 26 (2), pp. 139-146, 1990.
2. W.J. Haws, New Trends in Powder Processing Beryllium-Containing Alloys, Journal of Metals, vol. 52 (5) pp. 35-37, 2000.
3. J.M. Marder, Current Applications of Beryllium Manufactured by P/M Techniques, in Aerospace and Defense Technologies, Seattle, WA, Nov. 1989, vol. 2, pp. 133-136, 1991.
4. J.M. Marder, Powder Metallurgy Beryllium, in ASM Handbook, Tenth Edition, vol. 7, Powder Metal Technologies and Applications, Publ. ASM International, Materials Park, OH, pp. 941-946, 1998.

A. J. Stonehause and J.M. Marder, Beryllium, in ASM Handbook, Tenth Edition, vol. 2, Properties and Selection: Nonferrous Alloys and Special-Purpose Materials, Publ. ASM International, Materials Park, OH, pp. 683-687, 1990.

5. L.A. Grant and R.E. Hardesty, Fabrication of Stable Lightweight Beryllium Optical Support Structures, SPIE, vol. I335, Dimensional Stability, pp. 140-155, 1990.
6. M. Hunt, Surprising Beryllium, Materials Eng., vol. 105, pp. 46-49, 1988
7. J.J. Blakeslee, Metalworking IV: Forming, in Beryllium Science and Technology, vol. 2, Eds. D. R. Floyd and J. N. Lowe, Publ. Plenum Press, New York, NY, pp. 107-124, 1979.
8. Designing with Beryllium, Brush Wellman Report, 17876 St. Clair Ave., Cleveland, OH 44110, 2001.
9. L.A. Grant Forming of Beryllium, in ASM Handbook, Ninth Edition vol. 14, Forming and Forging, Publ. ASM International, Materials Park, OH, pp. 941-946, 1988, (Fifth Printing, 1998).
10. W.W. Leslie, Metalworking I: Rolling, in Beryllium Science and Technology, vol. 2, Eds. D. R. Floyd and J. N. Lowe, Publ. Plenum Press, New York, pp. 57-66, 1979.
11. J. A. Henkener et al., The Mechanical Behavior of Cross-Rolled-Beryllium Sheet, NASA TM-4397, NTIS-N9233485, October, 1992.
12. V.P. Krivko etal., The Effect of Annealing on the Mechanical Properties and the Structure of Beryllium Foil , Metal Science and Heat Treatment, vol. 33, (1-2), pp. 12-14, Jan., 1991.
13. J.E. Smugeresky, in Encyclopedia of Materials Science and Engineering, vol. 1, Publ. Pergamon Press Ltd., pp. 289-294, 1986.
14. B.L. Ferguson, Extrusion of Metal Powders, in ASM Handbook, Tenth Edition, vol. 7, Powder Metal Technologies and Applications, Publ. ASM International, Materials Park, OH, pp. 621-631, 1998.
15. P. Loewenstein, Metalworking II: Extrusion, in Beryllium Science and Technology, vol. 2, Eds. D. R. Floyd and J. N. Lowe, Publ. Plenum Press, New York, pp. 67-82, 1979.
16. W. W. Beaver and K. G. Wikle, Mechanical Properties of Beryllium Fabricated by Powder Metallurgy, Trans., AIME, vol. 200, pp. 559-573, 1954.
17. ASM Committee, in Metals Handbook, Ninth Ed., vol. 2, Properties and Selection: Nonferrous Alloys and Pure Metals, Publ. ASM International, Materials Park, OH, p. 718, 1979.
18. ASM Committee, Forging of Beryllium in Metals Handbook, Sixth Edition vol. 5, Forging, and Casting, Publ. ASM International, Materials Park, OH, pp. 132-133, 1970.

A. F. Hayes, Metalworking III: Forging, in Beryllium Science and Technology, vol. 2, Eds. D. R. Floyd and J. N. Lowe, Publ. Plenum Press, New York, NY pp. 83-105, 1979.

19. G. Glenn and A. F. Hayes, New Forging Techniques for Beryllium, Metal Progress, vol. 95 (3), pp. 131-139, 1969.
20. ASM Committee on Forming, Spinning, in ASM Handbook, Ninth Edition vol. 14, Forming and Forging, Publ. ASM International, Materials Park, OH, pp. 599-604, 1988, (Fifth Printing, 1998).
21. ASM Committee, Three-roll Forming, in ASM Handbook, Ninth Edition vol. 14, Forming and Forging, Publ. ASM International, Materials Park, OH, pp. 616-623, 1988, (Fifth Printing, 1998).
22. ASM Committee, Stretch Forming, in ASM Handbook, Ninth Edition vol. 14, Forming and Forging, Publ. ASM International, Materials Park, OH, pp. 591-598, 1988, (Fifth Printing, 1998).
23. ASM Committee, Wire, Rod, and Tube Drawing, in ASM Handbook, Ninth Edition vol. 14, Forming and Forging, Publ. ASM International, Materials Park, OH, pp. 330 to 342, 1988, (Fifth Printing, 1998).
24. J.P. Denny, Metalworking V: Wire Drawing, in Beryllium Science and Technology, vol. 2, Eds. D. R. Floyd and J. N. Lowe, Publ. Plenum Press, New York, NY, pp. 125-133, 1979.
25. H.D. Hanes and A.J. Stonehouse, HIP Beryllium Achieves Full Commercial Status, Metal Powder Report, vol. 42 (10), 1987; also <www. Brushwellman.com>.
26. J.M. Marder, Production of Beryllium Powders, in ASM Handbook, Ninth Edition, vol. 7, Powder Metal Technologies and Applications, Publ. ASM International, Materials Park, OH, pp. 202-205, 1998.
27. T. P. Clement etal., Near-Net-Shape Processing Cuts Cost of Beryllium Optics, Advanced Materials and Processes, vol. 141 (3), pp. 37-40, 1992.
28. D.H. Hashiguchi, etal., Properties of Beryllium Consolidated by Several Near-Net Shape Processes, J. Mater. Shaping Technol., vol. 7 (1), pp. 23-31, 1989.
29. S. Benshuang and S. Xinghai, Beryllium Benefits from CIP/HIP Pressing, Metal Powder Reports, vol. 51 (5), pp. 28-30, 1996.
30. P. Clements, How the Beryllium Industry is Building New Markets by Applying Isostatic Processing Technologies, in Proceedings of the 4th International Conf. On Isostatic Pressing, Stafford-Upon-Avon, UK, pp. 18-1 to 18-11, 1990.
31. C.G. Skillern et al., Production of Beryllium Mast Mounted Sights Using Near Net Shape Technology and Chemical Milling, in Aerospace, Refractory, and Advanced Materials Advances in Powder Metallurgy, vol. 6, Publ., Metal Powder Industries Federation, Princeton, NJ, pp. 381-389, 1991.
32. C.M. Bugle and N. Stroud, Rapid Net-Shape Forming of P/M Parts, Advanced Materials and Processes, vol. 158, (1) pp. 43-45, 2000.
33. Machining Beryllium Metal, Brush Wellman, Inc. Report, Second Revision, November10, 1982,
34. J.E.J. Bunce and M. Hill, Machining, in Beryllium Science and Technology, vol. 2, Eds. D. R. Floyd and J. N. Lowe, Publ. Plenum Press, New York, pp. 177-196, 1979.

35. G.R. Paul, Fabrication and Techniques of Beryllium Metal Removal, paper 670803, in Aeronautic & Space Engineering and Manufacturing Meeting, Society of Automotive Engineers, Inc., Los Angeles, CA, October 2-6, 1967.
36. D.V. Gallagher and R.E. Hardesty, Machining of Beryllium, in ASM Handbook, Ninth Edition vol. 16, Machining, Publ. ASM International, Materials Park, OH, pp. 870-873, 1989, (fourth Printing, 1999).
37. E.W. Zimmers, CAD/CAM Applications in Machining, in ASM Handbook, Ninth Edition vol. 16, Machining, Publ. ASM International, Materials Park, OH, pp. 627-636, 1989, (fourth Printing, 1999).
38. S. Beitscher, Machine-Induced Surface Damage, in Beryllium Science and Technology, vol. 2, Eds. D.R. Floyd and J.N. Lowe, Publ. Plenum Press, New York, pp. 197-230, 1979.
39. R.E. Cooper, Fracture Mechanics, in Beryllium Science and Technology, vol. 1, Eds. D. Webster and G.L. London, Publ. Plenum Oress, New York, NY, pp. 1-114, 1979.
40. R.E. Cooper, Fracture Mechanics, in Beryllium Science and Technology, vol. 1, Eds. D. Webster and G.L. London, Publ. Plenum Oress, New York, NY, pp. 1-114, 1979.
41. L.B. Norwood, Application of Beryllium on the Space Shuttle Orbiter, SAMPE Journal, vol. 16, May/June, pp. 9-15, 1984.
42. D.H. Hashiguchi, Beryllium Machining Technique Evaluation, Brush Wellman Technical Report TR1036, February, 1992.
43. Hughes Standard Specification on Machining of Beryllium, Document HP 1-26, Hughes Aircraft Company, undated.
44. ASM Committee, Turning, Traditional Machining Processes, in ASM Handbook, Ninth Edition vol. 16, Machining, Publ. ASM International, Materials Park, OH, page. 135, 1989, (fourth Printing, 1999).
45. Properties of Pure Materials, Beryllium, in ASM Handbook, Ninth Edition vol. 2, Properties and Selection; Nonferrous Alloys and Pure Metals, Publ. ASM International, Materials Park, OH, pp. 717-718, 1979.
46. ASM Committee, Milling, Traditional Machining Processes, in ASM Handbook, Ninth Edition vol. 16, Machining, Publ. ASM International, Materials Park, OH, page 303, 1989, (fourth Printing, 1999).
47. T.L. Lievestro, Electrochemical Machining, in ASM Handbook, Ninth Edition vol. 16, Machining, Publ. ASM International, Materials Park, OH, pp. 533-541, 1989, (fourth Printing, 1999).
48. E.M. Langworthy, Chemical Milling, in ASM Handbook, Ninth Edition vol. 16, Machining, Publ. ASM International, Materials Park, OH, pp. 379-386, 1989, (fourth Printing, 1999).
49. H. Friedman, Photochemical Machining, in ASM Handbook, Ninth Edition vol. 16, Machining, Publ. ASM International, Materials Park, OH, pp. 387-393, 1989, (fourth Printing, 1999).
50. ASM Committee, Trepanning, Traditional Machining Processes, in ASM Handbook, Ninth Edition vol. 16, Machining, Publ. ASM International, Materials Park, OH, pp. 175-180, 1989, (fourth Printing, 1999).
51. Handbook of Adhesive Technology, Second Edition, (Revised and Expanded), Eds. A.Pizzi and K. L. Mittal, Publ. Marcel Dekker, Inc., New York, 2003.

52. L.H. Sharpe, Overview: Adhesives Technology, in Engineered Materials Handbook, vol. 3, Adhesives and Sealants, Publ. ASM International, Materials Park, OH, pp. 33-38, 1990.
53. R.C. Snogren, Space-Age Bonding Techniques—Part 2, Adhesive Bonding, Mechanical Engineering. Vol. 92, (5). pp. 33-38, 1970.
54. D.E. Packham, Microstructural Analysis, in Engineered Materials Handbook, vol. 3, Adhesives and Sealants, Publ. ASM International, Materials Park, OH, pp. 406-419, 1990.
55. M.A. Gauthier, Adhesive Materials, in Engineered Materials Handbook, vol. 3, Adhesives and Sealants, Publ. ASM International, Materials Park, OH, pp. 73-93, 1990.
56. J. Small, Fundamentals of Industrial Adhesives, Advanced Materials and Processes, vol. 123, (5), pp. 44-47, 2005.
57. R.W. Messler, Jr., Adhesives and the Bonding Process, in Joining of Advanced Materials, Publ. Butterworth-Heinemann, Boston, MA, pp., 143-180, 1993.
58. R.S.C. Acker, Manufacturing Use, Section 8 (a series of articles by various authors), in Engineered Materials Handbook, vol. 3, Adhesives and Sealants, Publ. ASM International, Materials Park, OH, pp. 681-725, 1990.
59. R.J. Switz, Joining I: Mechanical/Adhesive, in Beryllium Science and Technology, vol. 2, Eds. D. R. Floyd and J. N. Lowe, Publ. Plenum Press, New York, pp. 231-238, 1979.
60. C.V. Cagle, Surface Preparation for Bonding Beryllium and other Adherents in Handbook of Adhesive Bonding, Eds. C. V.Cagle, et al., Publ. McGraw-Hill Book Company, New York, pp. 21/1-21/10. 1973.
61. R.C. Fullerton-Batten, The Adhesive Bonding of Beryllium Structural Components, in Proceedings of Beryllium—77, Fourth International Conference on Beryllium, 4-7 October, 1977, London, England, Publ., The Metals Society, London, England, pp.40/1-40/17, 1977.
62. M.A. Salazar et al., Effects of Joining and Testing Parameters on the Adhesive Strength of Epoxy-Bonded Aluminum and Beryllium, Fusion Technology, vol. 35 (3), pp. 119-122, 1999.
63. R.E. Cooper, etal., in Proceedings of Beryllium—77, Fourth International Conference on Beryllium, 4-7 October, 1977, London, England, Publ. The Metals Society, London, England, pp. 39/1-39/6, 1977.
64. R.W. Messler, Jr., Mechanical Fastening in Joining of Advanced Materials, Publ. Butterworth-Heinemann, Boston, MA, pp. 23-61, 1993.
65. J. H. Bickford, in An Introduction to the Design and Behavior of Bolted Joints, Publ. Marcel Dekker, Inc., New York, NY,1990.