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THE FABRICATION OF BERYLLIUM - VOLUME I: A SURVEY OF CURRENT TECHNOLOGY

Manufacturing Research and Technology Division
Manufacturing Engineering Laboratory

NASA

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ABSTRACT

This report is concerned with the fabrication of beryllium and its alloys into space vehicle structures. The report summarizes currently used methods for fabricating the metal into sheets, rods, and other forms. Some of the difficulties that have been encountered in various aspects of fabrication, especially regarding the inherent brittleness of the metal, are enumerated along with the means that have been used to circumvent these problems. The survey includes 102 references to articles and papers in the unclassified literature, most of them having been published since 1960. The data on beryllium prior to 1960 have been covered in two reports issued by the Defense Metals Information Center, DMIC Reports 106 and 168.

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FABRICATION OF BERYLLIUM—VOLUME I: A SURVEY OF CURRENT TECHNOLOGY

The other Volumes of Technical Memorandum X-53453 are:

Vol. II. Forming Techniques for Beryllium Alloys

Vol. III. Metal Removal Techniques for Beryllium Alloys

Vol. IV. Surface Treatments for Beryllium Alloys

Vol. V. Thermal Treatments for Beryllium Alloys

Vol. VI. Joining Techniques for Beryllium Alloys

MANUFACTURING RESEARCH AND TECHNOLOGY DIVISION
MANUFACTURING ENGINEERING LABORATORY
RESEARCH AND DEVELOPMENT OPERATIONS

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The Battelle work was authored by A. F. Gerds and F. W. Boulger.

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SECTION I. INTRODUCTION

The technology of fabricating beryllium has increased rapidly in the past several years because of efforts in the missile and space programs of our country and other countries. This, coupled with previous efforts in the field of nuclear energy, has added greatly to our understanding of many of the problems involved in working with this material. Recent recommendations[1] by the Beryllium Committee of the Materials Advisory Board have urged the Department of Defense to "consider providing additional funds for appropriate flight hardware programs so that selected airframe components can be designed and constructed in both beryllium and more conventional materials. In this manner, the use of beryllium can be encouraged and needed experience gained without danger of compromising a large vehicle program." This approach, if followed, should greatly increase our knowledge and experience with beryllium and some of the problems involved in using the metal.

The literature through 1960 on the use of beryllium for structural applications was reviewed by Hodge[2,3] in two publications of the Defense Metals Information Center (DMIC). Although these reviews were not exhaustive coverages of the unclassified literature and generally omit the requirements of the Atomic Energy Commission for the metal and oxide, the fact that only 51 references are cited in DMIC 106, which covers the literature prior to 1958 and 186 references in DMIC 168 which covers 1958-1960, indicates the increased amount of effort in working with beryllium that has taken place in recent years. No doubt any general literature review written today would show a correspondingly longer reference list, indicating the large effort that has been expended on studying beryllium since 1960.

The purpose of this review is to summarize current techniques for fabricating beryllium into components and hardware parts, mainly for aerospace requirements. The source material is referenced so that the reader may obtain more intimate detailed knowledge of the techniques by studying the pertinent publications.

Beryllium is a metal of great interest to the aerospace program. The properties of the metal that make it so attractive are light weight, good rigidity and stiffness, and the ability to absorb heat. The metal has a density of only 1.85 g/cc, an elastic modulus of 4×10^7 psi, a melting point of 2345°F, and a specific heat of 0.46 cal/g. This combination of properties is not available in any other metal or alloy.

Because of the high modulus of elasticity and low density of beryllium, the metal is potentially very useful on a strength-to-weight basis, a criterion used extensively in the design of aircraft and spacecraft. This permits designing such craft for longer flights and for heavier payloads for the same weight of material.

Beryllium metal, as commercially available, is a material with poor ductility at room temperature which somewhat limits its present usefulness. This lack of ductility is caused by the fact that the hexagonal close-packed beryllium crystal has essentially only one (the basal plane) of three potential slip planes (basal, prism, and pyramidal) operating at room temperature.[4] In this respect, beryllium is similar to both zinc and magnesium for which the basal plane also is the only plane on which slip can occur at room temperature. Extensive plastic flow can occur in favorably aligned single crystals. Polycrystalline aggregates, such as are found in commercial metals, contain random orientation of grains, and such a condition leads to high stress concentrations at grain boundaries.[4] This occurs when a favorably oriented grain has deformed and an adjacent nonfavorably oriented one has not. Such resulting dislocation pileups lead to fracture of the material. This accounts for the low ductility at room temperature for both zinc and magnesium and probably also for beryllium. A good discussion of this also is given by Gelles, Nerses, and Siergiej.[5]

In addition, there is no useful phase transformation in beryllium as is found, for example, in ferrous alloys. Beryllium transforms from body-centered cubic to a close-packed hexagonal system[6] on cooling at approximately 30°F below the melting temperature of the metal which is 2345 °F.[7,8] Thus, each time the pure cast metal is reheated the grain size increases. Oxide films around the powder particles in commercially pure metal retard grain growth. These and other factors make it extremely difficult to produce sound, dense ingots when the metal is cast, which is usually in vacuum to minimize contamination.

The cast beryllium metal exhibits essentially no ductility at room temperature, contains large columnar grains and usually porosity in one form or other, and generally is extremely difficult to fabricate. Currently, a research investigation[9] is under way at the Beryllium Corporation to produce sound castings by melting in vacuum to produce ingots 4.875 inches in diameter by 10.0 inches long and 6.0 inches in diameter by 17.0 inches long. Using a bottom-pour furnace and a graphite mold lined with alumina to retard the radial flow of heat, relatively sound castings with relatively fine columnar grains are being produced. Factors that appear to affect the degree of soundness in castings include pouring rate, direction of heat flow, and temperature gradients in the mold. Two especially important factors having a direct bearing on successful fabrication of beryllium components are:

(1) Grain Structure. Vacuum hot-pressed block, which is the basic form from which nearly all other wrought forms of the metal are produced, has a random (isotropic) grain structure which has relatively little tendency toward grain boundary separation or delamination during fabrication. This grain is drastically changed to a very preferred orientation (anisotropic) upon working into other forms, i.e., sheets, extrusion, or forging. The wrought forms of beryllium with the highly preferred grain orientation are also the form most susceptible to intergranular cleavage, which results in delamination and spalling when improper fabrication methods are employed.

(2) Elongation vs. Ductility. The close-packed, hexagonal grain structure and limited slip planes at room temperature result in brittle fracture cleavage at a bend angle of approximately 10 degrees. This, on first glance would seem incompatible with a typical elongation of 10 to 15 percent at room temperature. Further confusing the issue is maximum elongation at 700°F which would in most materials be the optimum forming temperature. However, adequate intergranular slip for severe forming does not occur below 1250°F and the optimum forming temperature has been found to be between 1325°F - 1350°F.

This work is continuing and may yield some interesting and useful data.

SECTION II. AVAILABLE METAL AND ALLOYS

Beryllium metal is produced from the silicate ore, beryl, where it is present at approximately the 4 percent level. Because of its very high reactivity when hot, the ore cannot be smelted in the normal sense by a pyrometallurgical process into beryllium metal plus a slag.[10] The beryl ore is usually treated chemically in a multistage process to convert it to the pure oxide or hydroxide of beryllium. The two principal methods for extracting the beryllium from the ore are the sulfate process and the complex fluoride process. Brush Beryllium Company uses a modification of the sulfate process. This is somewhat similar to the process used at the former Degussa factory at Frankfort, West Germany. This plant later was moved to Proz, France, and now is operated by Pechiney. The complex fluoride process, invented by Copaux, is the method used at Murex, the factory operated for the United Kingdom Atomic Energy Authority. A modification of this method also is used to recover BeO from beryl by The Beryllium Corporation of America.

At Brush, the beryllium hydroxide is reduced to beryllium pebble metal by reaction with magnesium, the magnesium then is removed by vacuum melting to yield beryllium of commercial purity. The ingot is chipped, ground to powder, and then hot pressed to produce the commercial grade block. This form of beryllium or the powder before pressing is the principal source of metal used today for structural applications. A grade of powder and block with very similar composition and properties is supplied by the Beryllium Corporation.

The Degussa or Pechiney process consists of mixing the BeO/ $Be(OH)_2$ with carbon, extruding into sticks, using a wood-tar binder, calcining, and heating in chlorine to form $BeCl_2$. The crude chloride is purified by sublimation, fused with an equal weight of sodium chloride, and the melt electrolyzed at 350°C (662°F) in a nickel cell to deposite beryllium flakes. After removing from the cell, the flakes are leached free of melt in water, washed, and dried. The Murex process used in Great Britain differs only slightly from the Degussa or Pechiney process. The Pechiney metal is somewhat more pure than the commercial hot-pressed block as can be seen in Table I where analyses of some of the grades of beryllium are summarized.

All of the commercially available grades of beryllium, with the possible exception of the Pechiney superpurity flake, are essentially alloys of beryllium. As such, they have been shown to age harden and possess other attributes and characteristics of alloys.[11, 12] Recent

Table I. Typical Analysis of a Number of Grades of Beryllium Metal

Element	Composition (weight percent)*										
	Nuclear Grade	Brush Structural-Grade Powder or QMV Block		Brush[15] QMV Vacuum Castings	Berylco Structural-Grade Powder		Pechiney Commercial Purity			Vacuum-Cast Distilled	Ultra-High Purity Beryllium[16]
		SP-100-A	SP-200-A		P-12	P-20	Flake	Powder	Super Purity Flake		
Be	98.5**	98.5**	98.0**	99.0	98.5**	98.0	-	-	-	-	-
BeO	1.2	1.2	2.0	0.5	1.2	2.0	0.40	0.50	0.03	-	-
Al	0.14	0.14	0.16	0.14	0.14	0.18	0.03	0.03	0.001	0.0015	0.0020
Ag	0.0005	-	-	0.0010	-	-	0.002	0.002	-	-	-
B	0.0002	-	-	0.00020	-	-	0.0002	0.0002	0.0002	-	-
Cd	0.0002	-	-	0.0002	-	-	0.0002	0.0002	-	-	-
Ca	0.02	-	-	0.02	-	-	0.02	0.01	0.001	-	-
C	0.12	0.12	0.12	0.14	0.15	0.15	0.03	0.05	0.01	-	-
Cr	0.03	-	-	0.03	-	-	***	0.005	-	0.0001-0.0002	0.0001
Co	0.0005	-	-	0.0005	-	-	0.002	0.002	-	-	-
Cu	0.015	-	-	0.015	-	-	0.01	0.01	0.0005	< 0.0010	0.0005
Fe	0.16	0.16	0.18	0.15	0.15	0.20	0.03	0.05	0.002	0.0002-0.0003	0.0003
Pb	0.002	-	-	0.002	-	-	-	-	-	-	-
Li	0.0003	-	-	0.0003	-	-	0.0003	0.0003	-	-	-
Mg	0.06	0.08	0.08	0.08	0.08	0.08	0.005	0.005	0.0005	-	-
Mn	0.015	-	-	0.015	-	-	0.01	0.01	0.002	0.0010-0.0015	0.0005
Mo	0.002	-	-	0.002	-	-	-	-	-	-	-
Na	-	-	-	-	-	-	0.03	0.015	0.005	-	-
Ni	0.04	-	-	0.04	-	-	0.02	0.02	0.001	0.0001-0.0002	0.0002
N	0.05	-	-	0.03	-	-	-	-	-	-	0.0005
O	-	-	-	-	-	-	-	-	-	-	<0.0300
Si	0.10	0.10	0.12	0.10	0.08	0.08	0.03	0.05	0.002	<0.0020	0.0012
Zn	0.02	-	-	0.02	-	-	-	-	-	-	-
Other metallics	-	0.04†	0.04†	-	0.04†	0.04†	-	-	-	-	<0.0002
Other halogens	-	-	-	-	-	-	0.11(g)	0.05††	0.05††	-	-
Approximate cost/lb		$100		$75			$85	$228	$483		$2,700

*Maximum content.
**Minimum content.
***Not reported.
†Each.
††Expressed as chloride.

extensive work on the purification of beryllium by distillation and zone-refining techniques have been carried on by Kaufman, et al.,[1] at Nuclear Metals, Incorporated. These studies showed that the limiting amount of resolved shear strain for basal slip increased with purity. Purification eliminated brittle fracture cleavage at elevated temperature (above 1000°F) but not at room temperature.

The more commonly quoted sizes and weights for commercially pure beryllium which are available are listed below:

Vacuum hot-pressed block	≤ 12,000 lb
Cross-rolled sheet	36 in. x 96 in.
Extrusions	Various cross sections 20-ft long
Forgings	≤ 200 lb (rolled ring)

(1) Vacuum Hot-Pressed Block. The most common form of beryllium material is vacuum hot-pressed block. This is produced by compacting and sintering beryllium powder in a mold at 1050°C at a pressure of 100 to 200 psi. This product is primarily used where high mechanical properties are not required and as starting material for producing extrusions, forgings and cross-rolled sheet.

(2) Cross-Rolled Sheet. A number of techniques for producing sheet and plate have been attempted in order to improve the physical and metallurgical properties, especially those influenced by crystal orientation. Methods such as (a) hot unidirectional or cross rolling, (b) bare rolling, (c) pack rolling, (d) hot rolling of canned powder, (e) ring rolling, (f) forging flats, and (g) slicing powder compacts have been investigated, with the most common method used today being hot rolling.

The exact procedure for rolling the sheet by the cross-rolled method is described in Reference 13. Mechanical properties of the sheet and the effects resulting from the various processes may also be found in Reference 13. Guaranteed minimum properties of commercial beryllium cross-rolled sheet are 50,000 psi yield, 70,000 psi tensile ultimate and 5 percent minimum elongation in the plane of the sheet.

Cross-rolled sheet may be procured in different forms. Foil sheet can be ordered in thicknesses down to .003 in. Standard sheet is produced in thicknesses between .020 and .25 in., and plate is available up to approximately 1-in. thick at present. Foil is limited mostly by cost, with the thinnest gage being many times the cost of the more common sheet gages.

(3) Extrusions. The most successful method of producing beryllium shapes is by extruding. The conventional method for extruding beryllium has been to extrude a steel-jacketed billet. The process is explained in Reference 13. The resistance of beryllium to flow, K, is the important variable in the extrusion process. K varies with temperature, friction, and tool geometry. A plot of K vs. temperature is shown on page 13 of Reference 13. The plot indicates that the K for beryllium at 1800°F is about equal to that of cold-rolled steel, which permits using mild steel billets for preliminary extrusion experiments.

Nuclear Metals Inc. has successfully extruded a number of shapes including channels. The channel sections have been extruded in thicknesses of 0.12, 0.09 and 0.06 in. up to 40 ft. Longitudinal mechanical properties are approximately 2 times the transverse properties. Another extensive study was conducted by Nuclear Metals to extrude finned beryllium tube. The results of this program are summarized in the references. The feasibility of co-extruding molybdenum and other metals with beryllium has also been demonstrated.

(4) Forgings. There are essentially two methods for producing high-integrity forgings. These two methods are (a) canned-powder method, and (b) press-forging method. The most successful of the two is the press-forging technique which was developed by the Ladish Co. Properties of the press forgings are available from metallurgical reports of the Ladish Co. Forging temperatures have been varied from 1300° to 2050°F, in the press-forging technique. The highest strengths were obtained by forging at 1375°F, with much higher ductility revealed in the specimen tests conducted at 800°F than at room temperature.

The canned-powder technique used by Wyman-Gordon is limited to rather simple shapes and consequently is not as promising as the press-forging technique. Its mechanical properties also are not as good as those obtained by the Ladish Co. The advantage of the method is its lower cost per part than other forging methods, since there is very little waste.

The method of forging beryllium fasteners is described in Reference 14.

The nearest approach to a commercial alloy of beryllium, excluding the commercial vacuum hot-pressed block, is the recently announced[15, 16] beryllium-aluminum alloys, called Lockalloys, containing from 24 to 43 weight percent aluminum. These multipurpose space-age metals developed by Lockheed Missiles and Space Company, Sunnyvale, California, are produced and marketed by the Dow Chemical Company under exclusive license from Lockheed. The Beryllium Corporation was granted an exclusive sublicense by Dow.

The Lockalloy alloys are claimed to combine the best properties of both aluminum and beryllium and are reported to be significantly more ductile than beryllium metal in the form of sheets and extrusions. Although the phase diagram of the beryllium-aluminum system indicates very limited solid solubility of aluminum and Beryllium in each other, there apparently is sufficient solubility to give more than a mechanical bond at the interphase boundaries. The increased ductility is not evident from elongation values obtained in tensile tests where about the same values are obtained for both beryllium and Lockalloy. However, in bend tests, the alloy sheet can be bent to a significantly greater degree than the commercially pure metal sheet as can be seen from the data in Tables II and III, where these materials are compared for both extrusions and sheet. Where fracture occurs at 7 to 9 degrees for beryllium extrusions, the Lockalloy can be bent up to 33 degrees before fracturing. Similarly, a two fold to threefold increase in bend ductility is obtained in Lockalloy sheet compared to beryllium sheet.

Compared to aluminum and magnesium, a weight saving is achieved by using Lockalloy sheet. Compared to beryllium, however, the use of Lockalloy results in a considerable weight penalty. The potential usefulness of these alloys will be determined by the degree of success achieved in designing around the lack of ductility found in commercially pure beryllium.

Table II. Mechanical Properties of Be-Al Extrusions at 75 °F[16]

Al (%)	Condition	E (10^6 psi)	TYS (10^3 psi)	CYS (10^3 psi)	TS (10^3 psi)	Elongation (%)	Bend* Angle (deg)		
							w = 1.25 in.	w = 0.50 in.	w = 0.25 in.
24	As extruded	37	72		88	3			
31	As extruded	34	78		83	2			
33	As extruded	34	76		82	4	8	14	33
33	Annealed	29	43		61	9	51	73	76
36	As extruded	32	75	71	76	1.2	15	12	5
36	Annealed	28	43	39	53	9	50	59	76
43	As extruded	29	63	59	69	1.5	17	17	27
43	Annealed	25	36	30	43	9	56	65	81
Be	As extruded						7	9	8

* Thickness = 0.058 in.

Three-Point Loading:
Span = 1.5 in.
Mandrel Radius 0.03125 in.

Table III. Mechanical Properties of Be-Al Sheet at 75°F[16]

Al (%)	Condition*	Longitudinal Properties E (10^6 psi)	TYS (10^3 psi)	TS (10^3 psi)	Elongation (%)	Bend* Angle (deg)	Transverse Properties E (10^6 psi)	TYS (10^3 psi)	TS (10^3 psi)	Elongation (%)	Bend* Angle (deg)	Rolling Direction
31	As received	30.4	67	79	4.6	67						Longitudinal
31	Annealed	29.8	41	61	6.5	>90						Longitudinal
36	As received	27.3	60	70	8.0	81						Longitudinal
36	As received	28.4	45	56	5.0		26.4	39	44	1.0		Bidirectional
36	Annealed	27.9	37	55	8.0	>90						Longitudinal
36	Annealed	28.6	40	52	4.0		26.9	36	45	2.5		Bidirectional
43	As received	25.8	55	64	12.0	85					54	Longitudinal
43	As received	24.2	37	44	4.0		27.2	37	48	8.0		Bidirectional
43	Annealed	24.6	33	50	13.0	>90					108	Longitudinal
43	Annealed						23.4	26	39	9.0		Bidirectional
Be, cross rolled	As received	42	53	74	9.0	26						Bidirectional

* Thickness = 0.020 in.; width = 0.5 in.

Three-Point Loading:
Span = 1.5 in.
Mandrel Radius = 0.03125 in.

SECTION III. PROPERTIES OF BERYLLIUM

Following are some pertinent properties of beryllium:

Density at 68°F (20°C)	=	1.848 g/cc (commercial metal ranges from 1.84 to 1.86 g/cc)
Melting point	=	2332°F*
Phase transformation	=	2300°F
Crystal structure	=	Hexagonal close packed up to 2300°F Lattice constants: ao = 2.2858 A co = 3.5842 A c/a = 1.5680 A Body-centered cubic from 2300°F to melting point; a_o = 2.55 A at 2320°F
Modulus of elasticity	=	40 to 44 million psi at 68°F
Poisson's ratio	=	0.024 to 0.030
Specific heat	=	45 cal/g/°C (at room temperature)
Heat of fusion	=	260 cal/g
Thermal conductivity	=	0.35 cal/cm/sec/°C
Electrical conductivity	=	38 to 43 percent IACS

*Darwin and Buddery[10] give 2341°F as the generally accepted melting point of beryllium (p 168). Other sources[7,8] give 2345°F as the melting point.

Resistivity	=	4 microhm-cm at 68°F for annealed material of commercial purity
		4 to 6 microhm-cm observed in quenched and aged material
Temperature coefficient	=	0.025/°C near room temperature
Emissivity coefficient	=	0.61 for solid and liquid at 6500 A

The tensile properties of commercial vacuum hot-pressed powder (also known as block) in three commonly available grades are as follows:[17]

	S-100-c	S-200-c	S-300-c
Ultimate Tensile Strength (min.), psi	35,000	40,000	40,000
Tensile Yield Strength (0.2 percent offset) (min.), psi	27,000	30,000	30,000
Elongation in 1 inch (min.), percent	1	1	1
BeO Content, wt percent	1	2	3

These properties are relatively low as are the mechanical properties of parts made from this block. However, when this material is worked by one of a number of ways, wrought products are obtained with the following properties in the major working direction:[5]

Ultimate Tensile Strength, psi	60,000 to 110,000
Yield Strength (0.2 percent offset), psi	40,000 to 70,000
Elongation in 1 inch, percent	10 to 20

Because of the much higher properties that can be obtained in wrought beryllium, extensive efforts have gone into devising fabrication methods to best produce these properties in beryllium. It should be kept in mind, however, that the transverse and short transverse

Hot consolidation of canned loose powder bypasses billet manufacture; this method is used in Great Britian to prepare cylindrical and tubular shapes for extrusion into tubing.[20] The 200-mesh beryllium powder is packed into graphite molds, the density being improved by vibrating the molds during compaction. This operation is performed in a dry box. Vacuum sintering at 1200° to 1230°C (2192° to 2245°F) produces billets ranging from 72 to 98 percent of the theoretical density for two grades of powder. After machining to accurate dimensions, the billets are sheathed in mild steel containers and extruded. Full density generally results after extrusion.

Very careful control[19] is required to prevent contamination by air remaining in the powder and also during evacuation of the can. Contamination from the graphite mold and the steel can is also a distinct possibility. It is advisable to compact loose powders under compression to avoid internal breaks or surface tears in the fabricated billet shapes.

The effect of a number of billet conditions on extruded beryllium rod is illustrated in Table IV, where properties of the rods produced are shown.[19] For all these extrusions the billet temperature was 1950°F and a reduction of 28:1 was achieved.

It can be seen that, on the basis of product yield, sintered powder billets are desirable in spite of slightly lower ductility found in rods produced from these billets compared with rods produced from unsintered billets. Billet densities of 90 to 98 percent of the theoretical density are preferred although lower densities can be fabricated if more care is taken.

1. Extrusion

Initially, extrusion techniques were developed for simple beryllium shapes such as round rods and smooth-wall tubing.[18] Today, extrusion is probably the most widely used and most successful of all forming processes for beryllium, especially for long complex structural shapes.

Extrusion is a fabrication process whereby a cylinder of metal is converted into a continuous length by forcing it to flow under high pressure through a restricted die opening, which is so shaped as to impart the required form to the product.[18] The extrusion may be either a rod or a more complicated shape.

Table IV. Properties of Extruded Beryllium Rod from Billets of Different Origin[19]

Billet Condition	Average Density (g/cc)	Average Tensile Strength (lb/in.^{2})	Average Yield Strength (lb/in.^{2})	Average Elongation (%)	Average Contraction (%)	Average Product Yield (%)
Cold pressed 70°F (not sintered)	1.22-1.31	90,700	43,900	13.4	13.4	43
Warm pressed 850°F (not sintered)	1.58-1.71	87,400	42,200	12.6	13.1	68
Pressureless-sintered (loose powder)	1.70-1.80	84,600	41,100	10.8	11.1	88
Hot pressed	1.84-1.86	83,700	40,900	10.3	10.4	89

A cross section of the confined space formed by the ram, liner, and die is shown in Figure 1. It can be seen that the billet remains under essentially hydrostatic compressive forces as the ram moves forward and the metal is forced through the die opening. The graphite plug or follower block between the beryllium billet and the extrusion ram permits all the metal to be extruded from the die without leaving the usual butt. This eliminates the need for sawing or shearing which is objectionable from a health point of view. The graphite follows the beryllium in a powdery form, sometimes with violence. The smaller the die opening (billet size and extrusion temperature being unchanged), the greater the pressure required to move the material through the restrictive opening. The relationship is not linear, being based on the equation

$$P = K \ln R,$$

where

P = punch pressure required to move the material
K = resistance of the metal to flow. K varies with temperature, friction, and tool geometry.

The force required to move the ram is

F = P times cross sectional area of billet.

Because of the effects of friction, the greater the length of the billet, the greater the force needed to move the billet. Therefore, the billet size must be compatible with the maximum capacity of the extrusion press.

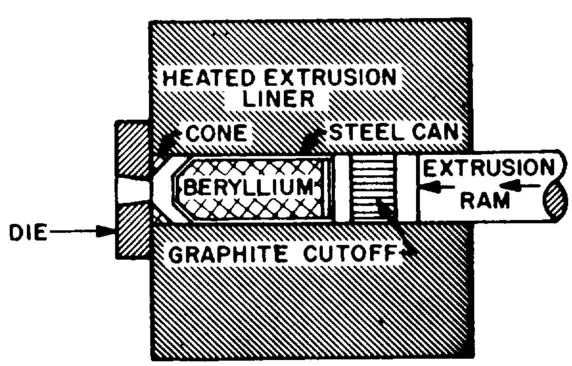

Figure 1. Press Assembly for Extrusion of Be Rods[18]

Figure 2 gives extrusion constants, K, as a function of temperature, for a number of materials including beryllium. This figure shows that the extrusion constant for beryllium at approximately 1800°F is approximately equal to that of cold-rolled steel at the same temperature. This is a fortunate relationship in that it permits using mild steel billets instead of the much more expensive beryllium billets for preliminary extrusion experiments.

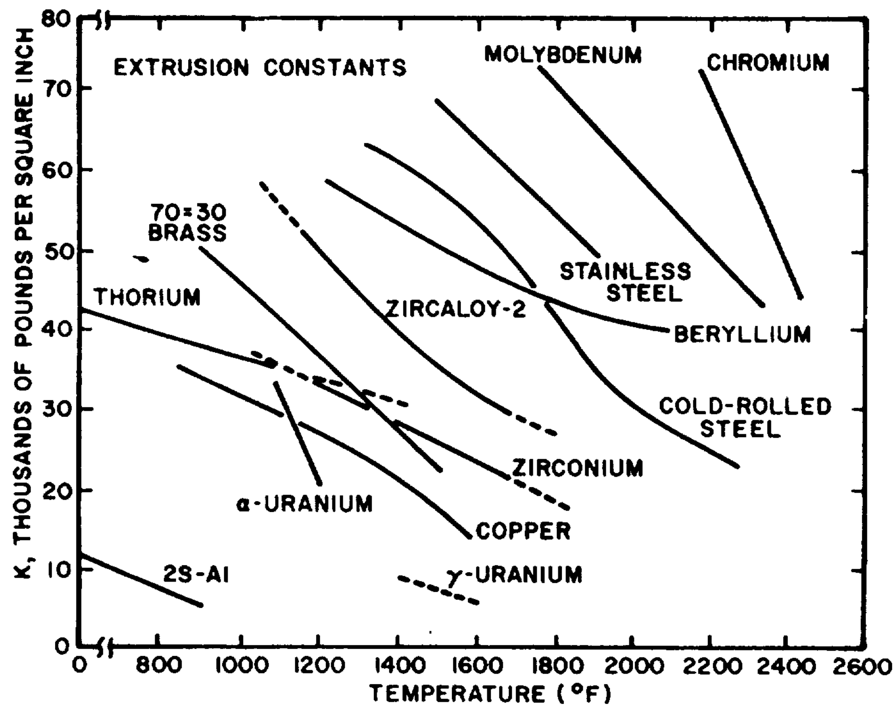

Figure 2. Extrusion Constants[18]

Beryllium is extruded with a conical die to ensure a smooth streamlined flow of metal in the extrusion. The conical shape can be achieved either by actually shaping the die or by causing glass powder to be trapped against a flat die to form a contoured approach to the opening of the die. The glass allows relatively inexpensive dies to be used by providing an excellent lubricant and also insulating the billet to minimize chilling during extrusion.

Beryllium metal tends to gall and stick to the extrusion tooling and, once this action has started, to erode the die away completely by abrasion. A practical method of solving this problem is to jacket the beryllium billet with mild steel or other metallic material which can be removed from the extrusion product by mechanical or chemical means. Molten glass lubricants form a protective film between the jacket and the die.

A second problem involved in extruding beryllium is the non-uniform flow of metal in the center of the billet as compared with the surface.[18] This occurs because of the chilling that takes place when the hot billet contacts the cooler extrusion tooling. As a result, extrusions often are not reproducible from one to another, transverse cracking or "rattlesnaking" may occur in the extrusion, or the pressure may progressively increase during the course of extrusion until the extrusion press stalls. The chilling of the beryllium is minimized by cladding. In addition, copper plating is sometimes employed on the jacketing material to minimize frictional effects. The use of special lubricants containing mica or asbestos may be advantageous not only to reduce friction but as a means of insulation to reduce the chilling tendency. Fast extrusion rates also minimize chilling of the billet.

The use of cladding on beryllium billets essentially solves the toxicity problem that would be present in extruding bare baryllium although this increases processing costs. Furthermore, the use of cladding increases development costs and development time to produce die designs that compensate for the varying thickness of cladding covering the extrusions.

Guest, et al.,[21] describe a pilot plant and processes for extruding commercially pure beryllium rods, tubing, and sections. They machined billets, produced by pressureless sintering, to an appropriate size before sheathing them in mild steel. For extruded lengths up to 10 feet, it was found desirable to extrude directly into guide tubes having a clearance of approximately 0.08 inch to keep the tube or rod straight. Their extrusion lubricant was flake graphite in an oil carrier. The tubes produced were used in support of the United Kingdom Atomic Energy Program. Where extremely close tolerances were required, postextrusion machining, drilling, and reaming operations were carried out.

Hessler and Steele[22] described experiments carried out at The Beryllium Corporation to convert ingots made by electro-beam melting directly into sheet bar for subsequent rolling into sheet. Following is the chemical analysis specification of the beryllium used for these studies:

Element	Maximum Weight (%)
BeO	0.50
C	0.10
Fe	0.15
Al	0.15
Si	0.10
Ni	0.04
Mg	0.08
Cr	0.03
Mn	0.03
Cu	0.05
Others (each)	0.01

Sound ingots were obtained by selectively sectioning cast ingots after careful inspection for defects. The selected sections were turned to approximately 2.5 inches diameter and then canned in a Type 304 stainless steel container with a nickel liner. The clad ingots were extruded at 1750° to 1950°F (ram speed 0.27 inch per second) into sheet bars 2.0 inches wide by 0.5 inch thick. This is equivalent to a reduction ratio of approximately 4.8:1. Bars extruded at 1850°F showed at least partial recrystallization; a similar bar extruded at 1750°F showed no recrystallization. Therefore, extrusion temperatures of 1850° or 1950°F appear desirable. The bars produced were suitable for cross rolling into sheet.

Figure 3 shows the cross sections of a variety of shapes extruded at Nuclear Metals, Inc., from commercially pure beryllium.[18] Using vacuum hot-pressed block generally of Grade QMV-200 or its equivalent, the cylindrical beryllium billet is encased in a mild steel can. The billet size is chosen so that its cross-sectional area is approximately 16 to 20 times greater than that of the extrusion although reductions ranging from 12:1 to 40:1 have been used.

If a hole is required in the extrusion, (Figure 3, items A, G, and I) an inner sleeve is used to accommodate the mandrel. Details of this method are shown in Figure 4 where the cross section of a canned billet with an inner sleeve is pictured.

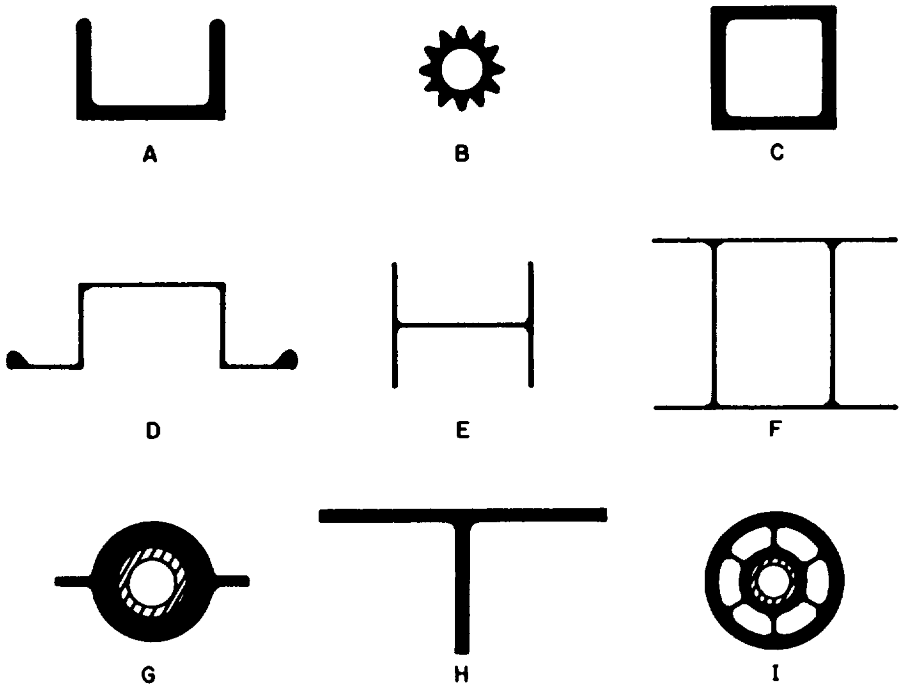

Figure 3. Extruded Beryllium Cross Sections[18]

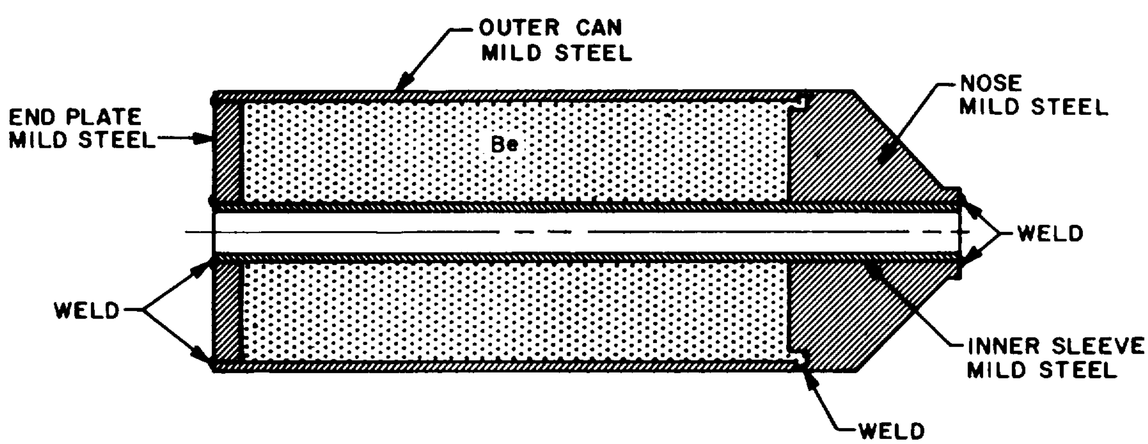

Figure 4. Sketch of Extrusion Billet[18]

The U-channel shown in item A of Figure 3 is 1 by 1.5 inches and was extruded in thicknesses of 0.120, 0.090, 0.060, and 0.040 inch in lengths up to 40 feet. As might be expected, the longitudinal tensile properties are considerably higher than the transverse properties as the following summary shows:

	Yield Strength (psi)	Ultimate Strength (psi)	Elongation (%)
Longitudinal	50,500	96,200	7.0
Transverse	28,000	52,400	1.0

A group of 20-foot-long U-channels produced in a pilot production run at Nuclear Metals, Inc., is shown in Figure 5.

The finned beryllium tube (Figure 3, item B) formed through a shaped die had a 0.5 inch diameter hole and measured 0.75 inch from tip to tip of the fins. The wall between the fins was approximately 0.03125 inch thick. The following burst strengths were found for the tubes as extruded and after etching to remove minor surface imperfections:

Condition	Hydrostatic Pressure on ID (psi)	Calculated Hoop Stress (psi)
As Extruded	4,310	29,200
1/2 Mil Etched Off	8,690	42,800
2 Mils Etched Off	16,840	97,100

These data show that it is advisable to etch beryllium after fabrication to remove approximately 0.002 inch from all surfaces of fabricated parts. Presumably the improvement results from reducing surface imperfections.

As an example of the precision that can be achieved in extrusion, the dimensional control on the inside diameter was ±0.001 inch and, with a honing operation after extrusion, could be held to 0.0002 inch. The wall thickness was held between 0.035 and 0.040 inch limits, and the outside diameter (across fin tips) was within ±0.005 inch.

Spiral-finned beryllium tubes were produced by extrusion on this job (Figure 6). The tubes are 24 inch lengths cut from 13 foot long extrusions. They were produced by the following three methods:

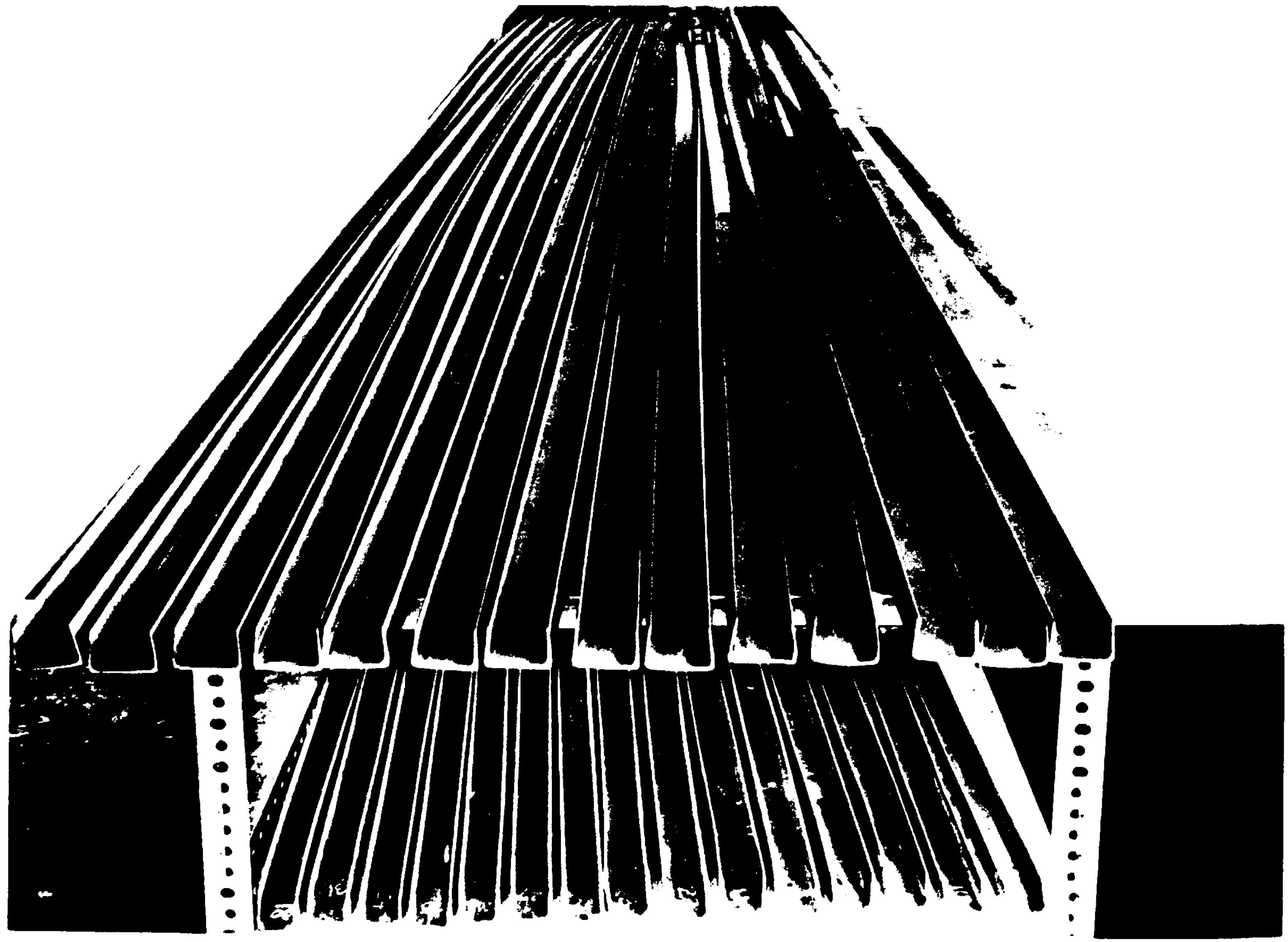

Figure 5. Beryllium U-Channels, Each 20 Feet Long, Produced in a Pilot Production Run[18]

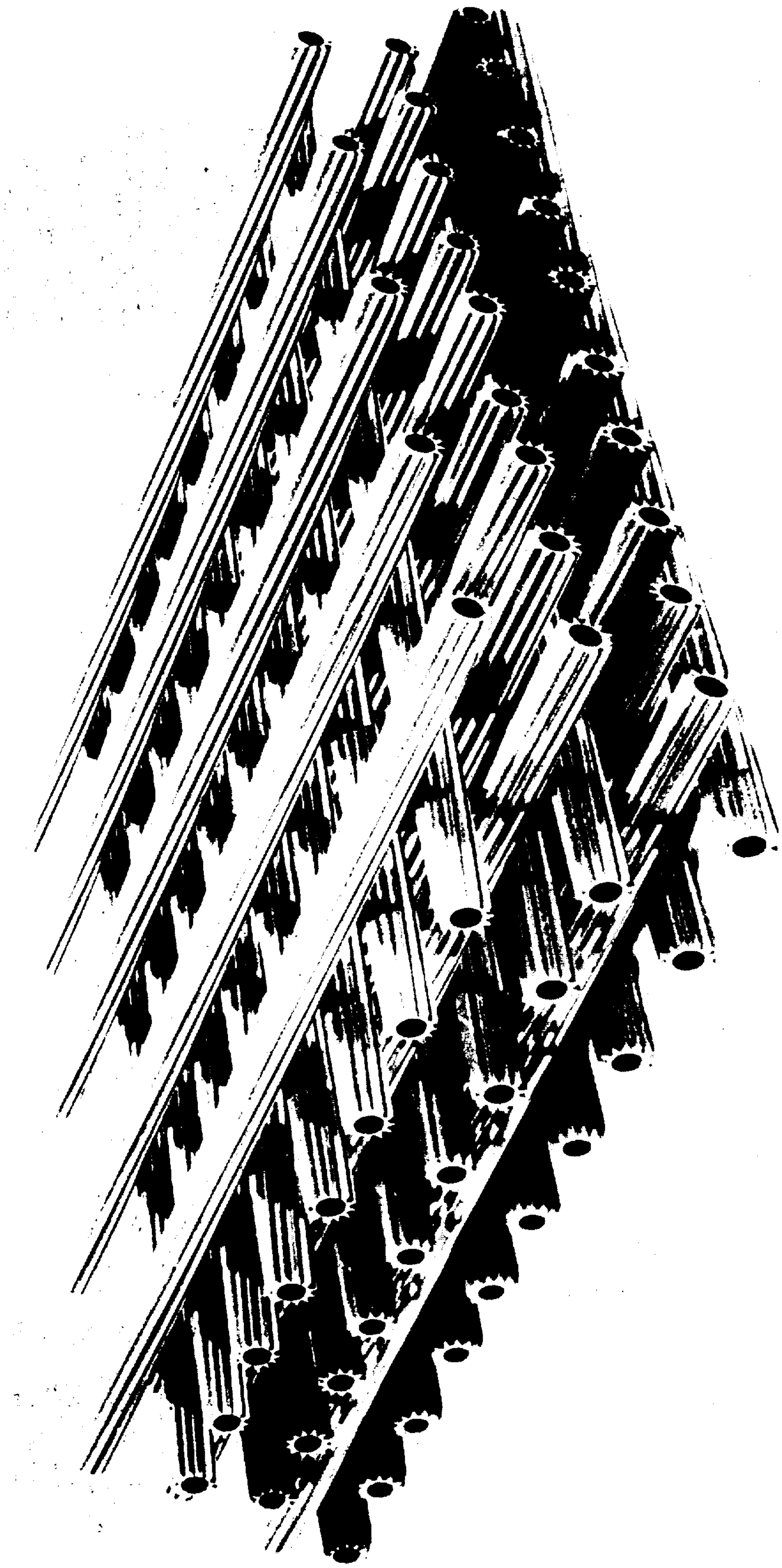

Figure 6. Beryllium Spiral-Finned Tubes Produced in 24-Inch Sections Cut from 13-Foot Extruded Lengths[18]

a. Filled Billet Method

The cross section of the beryllium extrusion billet has the same relative shape as the cross section of the extruded product desired, but the area is 16 times as great.

b. Modified Filled Billet

The ribs are formed as in Method 1, but the inside diameter is contoured by use of a mandrel.

c. Shaped Tooling

The contour of the beryllium rib is formed during the extrusion process by a shaped die; the inside diameter is controlled by use of a mandrel.[18]

Item C in Figure 3 is a square tube 1.0 by 1.0 by 0.100 inch. It was extruded with a floating square mandrel with a shaped die to develop the tooling alignment technique required to produce item F.

The original design of item D included six inside corners. This arrangement would make feeding of these corners, during extrusion with proper clad distribution, extremely difficult. The design was modified in conference between the designer and fabricator (Figure 3) to a shape that could more readily be extruded and still serve the required design purpose.

The I-beam section (Figure 3, item E) has been extruded in .10 by 1.5 by 0.100 inch size. It also has been extruded with a 0.060-inch wall. The wall thickness was further decreased to 0.030 inch by chemical milling.

Item F in Figure 3 is a combination of items A and C, and the techniques developed for them have been programmed into the die design and process steps for this extrusion.

The two-finned tube of beryllium (Figure 3, item G) has a coextruded cladding of columbium, 0.005 inch thick on the inside diameter bonded to the tube. If desired, the columbium cladding can be increased in thickness along the length of the tube while the beryllium thickness decreases, so as to phase into a tube end composed of columbium only. A billet that might be used for such a transition joint is shown at the left in Figure 7, and the expected shape of the two components after extrusion is shown at the right in the same figure.

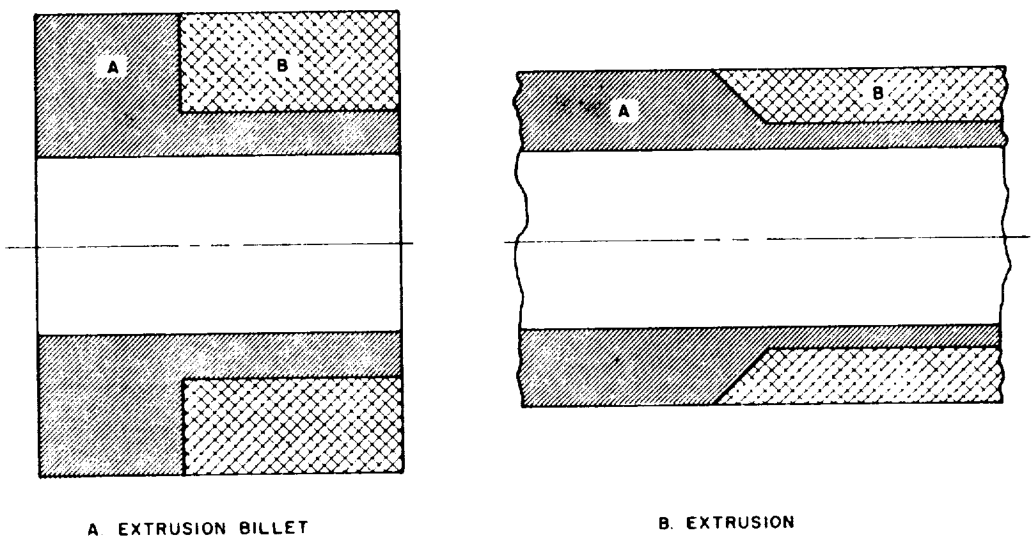

Figure 7. Transition Joint of Columbium (A) and Beryllium (B) Metallurgically Bonded by Coextrusion[18]

Items H and I in Figure 3 had not yet been produced when the report[18] was written. Their production probably will not present any greater difficulties than were encountered in extruding most of the other items whose cross sections are shown in Figure 3.

2. Production of Sheet

Extensive work on producing sheet beryllium has been carried on by both commercial producers of beryllium, Brush Beryllium Company and The Beryllium Corporation, in the United States as well as by other companies here and abroad. At present, rolling is confined to the fabrication of sheets, flats, and bars. Sheets approximately 2 feet by 6 feet by 0.020 inch and thicker have been rolled with some degree of reproducibility and quality.[5] One producer reported as early as December 1960, that commercially pure beryllium sheets measuring 24.0 by 84.0 by 0.040 inches had been produced.[23]

Beryllium sheet and plate are produced by a number of techniques,[19] generally to obtain different properties, particularly those properties influenced by crystal orientation. These methods include the following:

Hot (canned) unidirectional or cross rolling

Warm or bare rolling

Pack rolling

Hot rolling of canned powder

Ring rolling

Forging flats

Slicing powder compacts.

The most common breakdown method is hot rolling. Starting generally with vacuum hot-pressed beryllium slab made from powder, the slab is machined to the dimensions required to make the final sheet. It is inspected by X-ray, radiographic, ultrasonic, and liquid penetrant techniques before rolling to eliminate the possibilities of cracks or other imperfections in the rolled sheet. Then the slab is clad, usually by the picture frame technique. Mild steel frames generally are used although Wikle, et al.,[24] showed in studying 13 materials for use as cladding that rimmed steel probably was equally satisfactory. The rails of the mild steel picture frame often are of the same thickness and width as the beryllium block, and the cover plates are usually approximately half as thick as the beryllium. Wikle, et al.,[24] have reported that machining the beryllium block 0.030 or 0.040 inch thicker than the picture frame rails has effectively lessened the incompatibility of steel and beryllium, since the first few passes seat the beryllium block quite solidly in the frame, thus minmizing an initial allowance between the beryllium block and the frame. The entire assembly is welded tightly, and the interfaces between the beryllium and the steel cladding are often covered with a parting compound which may be graphite, chromium sesquioxide, or other dispersions. Sometimes the residual air is removed from the frames after welding, but this ordinarily is not necessary when rolling beryllium block

Hessler and Steele[22] also converted electron beam melted beryllium ingot into sheet bar for final rolling by a direct-rolling technique. Cladding the selected sections from the cast ingot in a stainless steel can with a 0.75-inch wall and welded end plugs, the round ingot was converted to a 2.0-inch square rod using grooved rolls. The rod was then flat rolled to 0.5 inch thick sheet bar. Rolling was done at 1475° to

1600°F, and the resulting sheet bar had a recrystallized structure. The recrystallization may have resulted from the heavy reduction produced at lower temperatures. Similar extrusions, which were produced at 1750° to 1950°F, did not completely recrystallize. However, some unrecrystallized deformed beryllium was found at the geometric center of the rolled sheet bar.

Final rolling of the beryllium ingot sheet bar, produced either by extrusion or rolling, was performed on a two-high laboratory mill having rolls 9.0 inches in diameter by 9.0 inches wide. Sections approximately 3.0 by 2.0 by 0.4375 inches were machined from the sheet bar and clad in a thick-walled steel picture frame. Sheet bar separated from the steel frame by Type 304 stainless steel strip, or welded in a frame made from Type 304 stainless steel, could generally be cross rolled at 1550° to 1650°F without cracking to produce strip 0.075 to 0.090 inch thick. Reductions of approximately 5 percent per pass appear preferable to relatively heavy reductions of approximately 25 percent per pass. Ingot converted to sheet bar by rolling appeared preferable to ingot converted by extrusion based on the appearance of the final rolled strip.

One procedure[23] is to roll the billet at 1400° to 1500°F, using a two-high or four-high mill, to a length which will become the final width of the sheet. The partially rolled assembly is then rotated 90 degrees and rolled further until the finished gage is achieved. Another procedure[20] for manufacturing sheet is to roll the clad billet at 1400° to 1450°F (15 percent reduction per pass) rotating alternately 90 degrees between passes until the width of the mill is reached, then alternating 180 degrees per pass until the desired length is attained. By this process, sheet up to 36.0 by 96.0 inches in gages of from 0.020 to 0.250 inch have been made. Total thickness reductions ratios greater than 100:1 have been obtained in rolling. Slow cooling after the final rolling pass is desirable to minimize cracking of the beryllium. Cracking may occur because the coefficient of expansion of steel is less than that of beryllium, thus producing high tensile stresses in the beryllium during cooling, especially if the beryllium is bonded to the steel frame.[23] The use of a parting compound helped to minimize welding.

Weismantel and Kopelman[25] found that after breakdown rolling at 1500°F, optimum mechanical properties were developed by final reductions performed at 1400°F (Table V). However, there is a limit to the deformation that the material can endure at 1400°F without reducing the final physical properties. Such sheet showed good ductility

Table V. Typical Properties of Beryllium Sheet Metal as Affected by Processing Variables[25]

Series	BeO Content (%)	Breakdown Overall Reduction Ratio	Breakdown Roll Temp. (°F)	Final Roll Temp. (°F)	UTS ($lb/in.^2$)		Yield Strength ($lb/in.^2$)		Elongation (%)	
					Longitudinal	Transverse	Longitudinal	Transverse	Longitudinal	Transverse
1	1.20	5:1	1500	1500	68,000	69,100	47,100	46,800	9.5	10.1
2	1.90	5:1	1500	1500	71,200	74,500	52,100	51,800	11.8	10.7
3	1.20	5:1	1500	1400	78,800	76,100	59,100	55,800	14.1	13.5
4	1.90	5:1	1500	1400	78,000	76,200	62,500	61,300	13.0	12.1
5	1.20	5:1	1400	1400	72,200	75,400	53,000	54,700	12.0	18.4
6	1.20	15:1	1400	1400	70,800	74,600	61,500	64,200	13.0	9.5
7	1.20	5:1	1750	1500	67,600	69,100	47,600	46,700	8.7	10.3
8	1.90	5:1	1750	1500	73,000	73,900	50,700	51,700	10.4	10.1

in the plane of the rolled sheet, the elongation ranging from approximately 12 to 14 percent in both longitudinal and transverse directions at ultimate tensile strength levels of approximately 75,000 psi. The sheet containing 1.9 percent BeO had a slightly higher yield strength than that containing 1.2 percent BeO, but their tensile strengths were essentially the same in both the longitudinal and transverse directions.

Weismantel and Black,[26] in studying the rolling into sheet of commercially pure beryllium with two oxide contents, found that lower rolling temperatures produced higher ultimate tensile strength, higher ductility, and finer grain structures. Table VI indicates that minimum final rolling temperatures which produced the highest mechanical properties in sheet beryllium were 1435°F for beryllium with 1.90 percent BeO and 1350°F for beryllium with 1.25 percent BeO. Slightly higher strengths were obtained with materials containing the higher BeO content.

It is desirable and often necessary to rejacket the beryllium during rolling.[24] Reductions in thickness of 2:1 to 4:1 can generally be carried out with one jacketing with good results. Under 0.125 inch thicknesses, stiffer steels are sometimes used with more frequent rejacketing to obtain better surfaces.

Flattening and trimming of the beryllium sheet is done after it is removed from the cladding.[23] Roller levelling and stretcher straightening must be completed while hot to avoid cracking the beryllium sheet. However, creep flattening is probably the best method to use to flatten the sheet. This procedure consists of placing the sheet between heavy plates and heating the sheet hot enough for it to be deformed plastically by the weight of the plate. Flatness obtained by this method usually meets commercial tolerances.

Typical properties of commercial beryllium sheet are now 50,000 psi minimum yield strength, 70,000 psi minimum tensile strength, and 5 percent minimum elongation in the plane of the sheet. The short transverse ductility of the sheet is considerably lower than that found in the plane of the sheet.

Barrow and Craik[27] studied the fabrication of beryllium sheet by upset forging at 1050°C (1922°F). Sheets from 0.25 to 0.080 inch thick were formed by direct press forging at 1050°C (1922°F) followed by cross rolling at 800°C (1472°F). Their objective was to improve the third dimensional (short transverse) ductility of sheet beryllium, thus making the material more useful structurally.

Table VI. Summary of Tensile Test Data Obtained on Beryllium Sheet-Rolling Program[26]

Sheet Design	BeO Content (%)	Rolling Temperatures (°F) Breakdown	Rolling Temperatures (°F) Finish	Gage (in.)	Overall Reduction Ratio	Avg UTS (psi)	Avg YS (psi)	Avg Elongation (%)
AF-1	1.08	1525	1410	0.188	5.3:1	72,700	57,000	8.7
AF-1-0	1.90	1525	1410	0.188	5.3:1	67,900	62,300	3.88
AF-2	1.08	1410	1410	0.188	5.3:1	74,600	53,200	17.1
AF-2-0	1.90	1410	1410	0.188	5.3:1	60,800	59,800	1.04
AF-3	1.08	1750	1525	0.188	5.3:1	67,850	47,350	8.7
AF-3-0	1.90	1750	1525	0.188	5.3:1	70,255	51,900	7.2
AF-4	1.08	1525	1525	0.188	5.3:1	68,120	46,900	8.4
AF-4-0	1.90	1525	1525	0.188	5.3:1	73,000	52,000	10.1
AF-5	1.08	1525	1400	0.060	16.7:1*	74,250	57,600	15.6
AF-5-0	1.90	1525	1400	0.060	16.7:1*	72,900	61,650	10.47
AF-6	1.08	1400	1400	0.060	16.7:1*	72,400	61,350	10.4
AF-6-0	1.90	1400	1400	0.060	16.7:1*	74,700	65,400	8.96
AF-7	1.08	1500	1435	0.188	5.3:1	74,800	51,260	15.0
AF-7-0	1.90	1500	1435	0.188	5.3:1	78,600	57,975	18.5
AF-8	1.08	1350	1350	0.188	5.3:1	74,350	53,050	12.7
AF-8-0	1.08	1350	1350	0.188	5.3:1	72,880	51,750	11.4
AF-9 (reclad AF-4)	1.08	1525	1400	0.060	16.7:1	68,150	51,150	15.1
AF-9-0 (reclad AF-4)	1.90	1525	1400	0.060	16.7:1	68,300	55,900	11.59
AF-10 (reclad AF-3)	1.08	1750/1525	1350	0.060	16.7:1**	53,850	45,100	2.0
AF-10-0 (reclad AF-3-0)	1.90	1750/1525	1350	0.060	16.7:1**	64,200	47,450	6.4
AF-11 (reclad AF-1)	1.08	1525/1400	1350	0.060	16.7:1	67,200	57,300	11.0
AF-11-0 (reclad AF-2)	1.08	1400	1350	0.060	16.7:1	70,100	57,750	11.1
AF-12 (reclad AF-1-0)	1.90	1550	1400	0.060	16.7:1	68,950	53,450	7.9
AF-12-0 (reclad AF-2-0)	1.90	1500	1400	0.060	16.7:1	69,300	54,050	9.1
AF-13	1.26	1400	1400	0.188	5.3:1	72,050	51,900	14.0
AF-14	1.26	1400	1400	0.188	5.3:1	71,130	51,300	8.9
AF-15	1.26	1500	1500	0.188	5.3:1	71,390	46,493	16.2
AF-15-0	1.26	1500	1500	0.188	5.3:1	72,400	46,500	16.7
AF-16	1.26	1500	1500	0.188	5.3:1	70,200	47,450	10.2
AF-16-0	1.26	1500	1500	0.188	5.3:1	70,950	48,350	10.1
AF-17	1.26	1500	1500	0.188	5.3:1	65,630	47,500	6.0
AF-17-0	1.26	1500	1500	0.188	5.3:1	67,800	47,500	7.9
AF-19	1.26	1500	1400	0.060	16.7:1	71,450	60,150	19.5
AF-20	1.26	1500	1350	0.060	15.7:1	73,800	61,250	15.7
AF-21	1.26	1500	1400	0.060	15.7:1	72,300	57,933	13.1
AF-22	1.26	1500	1400	0.060	15.7:1	71,900	58,700	12.4
AF-23	1.26	1400	1400	0.060	15.7:1	71,200	55,230	16.8

*Direct reduction without recladding at 0.188-in. thickness.

**Reduced 10 to 15% at 1350°F instead of 5 percent used for other tests.

Using both Brush and Pechiney powders, their[27] procedure was to fill mild steel cans having 0.25-inch thick walls with loose-packed powders. The lids of the cans were welded into position, and reductions of cylindrical height up to 96 percent were then made by upsetting at 1050°C (1922°F). Press forging of 1.5 to 2.0 inch diameter by 1.0-inch high containers filled with beryllium powder was accomplished with a 400-ton press. Sheathed beryllium disks, about 3.5 inch diameter by 0.20 inch thick, could be formed by a single pressing. Small thicknesses, approximately 0.040 inch, by 5.0 inches in diameter could be obtained by pack forging. This pack forging technique consisted of preheating the sheathed pressings and press forging three or four of these in a stack. Larger size pressings were obtained from 4.0-inch diameter containers filled with loose-packed Brush powder and pressing on a 2000-ton press. Beryllium disks, 7.0 inches diameter by 0.25 inch thick, were produced from these pressings. Pack forging resulted in disks approximately 10.0 inches in diameter by 0.10 inch thick produced in a single press forging using platens preheated to 600°C (1112°F). Thinner sheet was produced by cross rolling the sheathed disks at 800°C (1472°F), and reheating between each 10 percent reduction in thickness. Sheet about 0.080 inch thick by 13.0 to 14.0 inches in diameter resulted from the rolling operations.

Sheet derived from powder was characterized by a mixed recrystallized structure with an average grain size of approximately 50 microns in the plane of the sheet and 12 microns through the thickness of the sheet. Sheet formed from ingot showed residual cold-working effects and distorted grains of approximately 270 microns average size in the sheet plane and 80 microns through the thickness of the sheet. This sheet showed no evidence of recrystallization. Annealing at 700° to 875°C (1290° to 1605°F) for 24 hours had no visible effect on the powder sheet but caused complete recrystallization in the ingot sheet. Equiaxed grains, approximately 80 microns average, were produced. Further grain refinement was achieved by open-press forging the preforged ingot sheet at 600°C (1110°F) followed by annealing for 12 hours at 750°C (1380°F). An average grain size of 60 microns resulted. Unfortunately, no tensile data were given.

3. Forging

a. Canned-Powder Method

One of the more promising methods for producing high-integrity forgings is by canning beryllium powder in mild steel, austenitic stainless steel, or nickel containers and forging at 1600°

to 1900°F.[28] Vibrations are used to obtain the highest packing density of the powder. Pressforging speeds comparable to those used for aluminum are employed (7 feet per minute for simple shapes; 1 foot per minute when an extrusion action is required). The high forging pressure is maintained for a brief controlled period to ensure proper densification followed by slowly cooling to room temperature. The canning material is removed either by pickling or machining. A variety of parts having thicknesses as small as 0.125 inch to as large as 12.0 inches have been forged. Parts up to approximately 100 inches diameter can be forged by this technique.

The process is limited to rather simple shapes such as disks, hemispheres, disk-shaped cylinders, truncated cones, flat plate, and long structural shapes having "L" and "C" cross sections. The process is not suitable for complex rib and web shapes. The most widely used production specification for commercial beryllium forged components is 30,000 psi tensile yield strength, 40,000 psi ultimate tensile strength, and 1 percent elongation.

One outstanding advantage of the canned-powder forging method is the lower cost per part, since very little waste due to scrap occurs. Machining scrap in parts fabricated by other methods can be 50 percent or more by weight. Thus, the saving in producing beryllium parts by the canned-powder forging technique might be approximately equivalent to reducing the price of the beryllium powder by 50 percent or more.

Cieslicki[28] also determined the influence of forging temperature on the mechanical properties of various shapes produced by the canned-powder techniques. The data in Table VII indicate that parts forged at 1600°F generally had slightly higher average strength and ductility values than those forged at 1900°F.

Data on properties obtained on the first 441 small parts of a hollow-bowl configuration forged by the canned-powder technique in a normal forging practice also were reported by Cieslicki.[28] All tests were made at the same location; the parts were made to the customer's specification of 30,000 psi yield strength, 40,000 psi ultimate strength, and 1 percent elongation. The test direction is the long transverse direction. Results of these tests are summarized in Table VIII and show that parts of good quality can be produced by this technique on a production basis.

Table VII. Strength and Ductility of Three Parts Forged at 1600° and 1900°F by the Canned-Powder Technique[28]

Forging Temp. (°F)	Part*	Average Yield Strength, 0.2% Offset (psi)	Average Ultimate Tensile Strength (psi)	Average Elongation (%)
1600	A	55,000	67,000	2.00
	B	36,400	58,900	1.93
	C	41,100	60,900	2.9
1900	A	36,100	53,400	2.25
	B	32,800	43,900	1.86
	C	38,600	52,200	1.2

* Part A - 90° angle beam, 14 in. long with legs 3.5 in. long by 0.625 in. thick.

Part B - Shaft, 12 in. long with cylindrical ends and the center 6 in. is square in cross section, 4 in. on a side. The cylindrical ends are flanged with a maximum diameter of 5 in. and a minimum diameter of 3 in.

Part C - A ring 4 in. thick with a maximum diameter of 8 in. and a 5 in. hole partially forged into the center. Three arms extend from the outside diameter, each 3 in. long by 0.75 in. thick. One arm is radial and two are roughly tangent to the inside circumference.

Table VIII. Range and Distribution of Room-Temperature Mechanical Properties for Beryllium Parts Forged by the Canned-Powder Technique[28]

Test Bars Removed From 441 Parts Having Hollow-Bowl Configuration

Number of Parts*	Tensile Yield Strength, 0.2% Offset (psi)	Number of Parts	Ultimate Tensile Strength (psi)	Number of Parts**	Elongation (%)
1	<29,000	5	<45,000	1	<0.5
84	29,000 - 35,000	121	45,000 - 49,000	3	0.5 - 1.0
189	35,000 - 39,000	195	49,000 - 55,000	44	1.0 - 1.4
131	39,000 - 45,000	45	55,000 - 59,000	55	1.4 - 2.0
29	45,000 - 51,000	36	59,000 - 65,000	99	2.0 - 2.6
3	51,000 - 55,000	8	65,000 - 69,000	96	2.6 - 3.2
1	55,000 - 59,000	4	>69,000	35	3.2 - 3.8
2	>60,000			28	3.8 - 5.0
				11	5.0 - 6.2
				3	6.2 - 6.8
				1	>6.8

* One yield determination not made.

** Only 327 elongation values reported since these only represent the presently used technique. Remaining 141 elongation values were not considered valid because of variations in testing technique.

b. Press Forging

Work performed at Ladish Company and reported by Hayes and Yoblin[29, 30] indicates that vacuum hot-pressed beryllium can be successfully forged in closed dies to provide an improved aerospace quality structural material for Air Force requirements. A positive method for keeping the beryllium in compression is necessary for forging operations, which normally develop extensive tensile stresses of high magnitude, to prevent cracking of the forgings. Initially, the beryllium billets were canned in 0.5 inch thick steel jackets. Forging temperatures were varied from 1300° to 2050°F. The commercial vacuum hot-pressed block was used to produce upset-forged beryllium. Height reductions of 85 percent were produced consistently over the full temperature range. The properties listed in Table IX indicate that highest strengths at room temperature and at 800°F were obtained by forging at 1375°F. Considerably higher ductility was obtained in the tests at 800°F than in those performed at room temperature.

Because of expense involved in fabricating and removing the jacket and for additional metallurgical reasons, efforts were made to forge unclad beryllium. One solution to the problem was through development of a suitable die design to provide the needed restraint during forging. This was accomplished in the following ways at Ladish: 1) spring-loaded dies, 2) independently actuated concentric punches, and 3) carbon-steel support rings. Dies were heated to 800°F and coated with Pate Oil Forging Compound No. 400 for this work. Beryllium blanks were etched for 20 minutes in an aqueous solution containing 3 percent H_2SO_4 and 3 percent H_3PO_4 and then coated with Chicago Vitreous Lubricant No. 325. If two or more forging operations were involved in producing a part, the parts were vapor blasted between operations prior to etching and recoating. The blanks were heated to 1400°F. A total of 61 different parts were produced, and the evolution of the tooling required to produce the parts is described in detail.[29] Most of the parts required two or more forging steps.

Figure 8 shows the principle of the steel support ring used to produce one of the cup forgings. The force used to deform the steel ring produces compressive stress on the surface of the beryllium work-piece. Figure 9 illustrates the ring-rolling technique used to produce another part.[29]

These authors[30] also discuss four ways of producing forging preforms. Table X gives the relative costs of converting powder or chips

Table IX. The Effect of Forging Temperature Upon the Tensile Properties of Hot-Pressed and Upset-Forged Beryllium[30]

Forging Temp. (°F)	Test Temp. (°F)	Yield Strength* ($lb/in.^2$)	Ultimate Strength ($lb/in.^2$)	Elongation in 1 in. (%)	Elongation of Area (%)
1300	80	48,500	78,600	13.5	14.2
1375	80	50,500	81,700	9.7	13.7
1450	80	42,500	77,000	16.0	14.0
1550	80	38,400	75,400	12.8	12.7
1650	80	32,800	69,500	9.3	6.7
1750	80	33,600	67,600	9.3	10.2
1900	80	33,300	63,800	7.5	8.1
2050	80	28,200	59,300	6.1	6.2
1300	800	30,800	32,300	21.6	48.4
1375	800	31,400	31,400	13.7	56.1
1450	800	27,700	31,200	30.8	63.1
1550	800	24,600	30,400	29.3	59.0

* 0.2 percent offset.

Table X. Comparison of Preforms Fabricated by Four Techniques[30]

	Complexity of Preform Possible	Relative Cost for Converting Powder or Chips to Forging Preforms	
		Small Quantities	Large Quantities
Cold press and sinter	Fair - good	Moderate	Low
Slip cast and sinter	Excellent	Low	Moderate to high
Chip compaction and sinter	Fair	Moderate	Low to moderate
Vacuum warm pressing	Good	High	Moderate

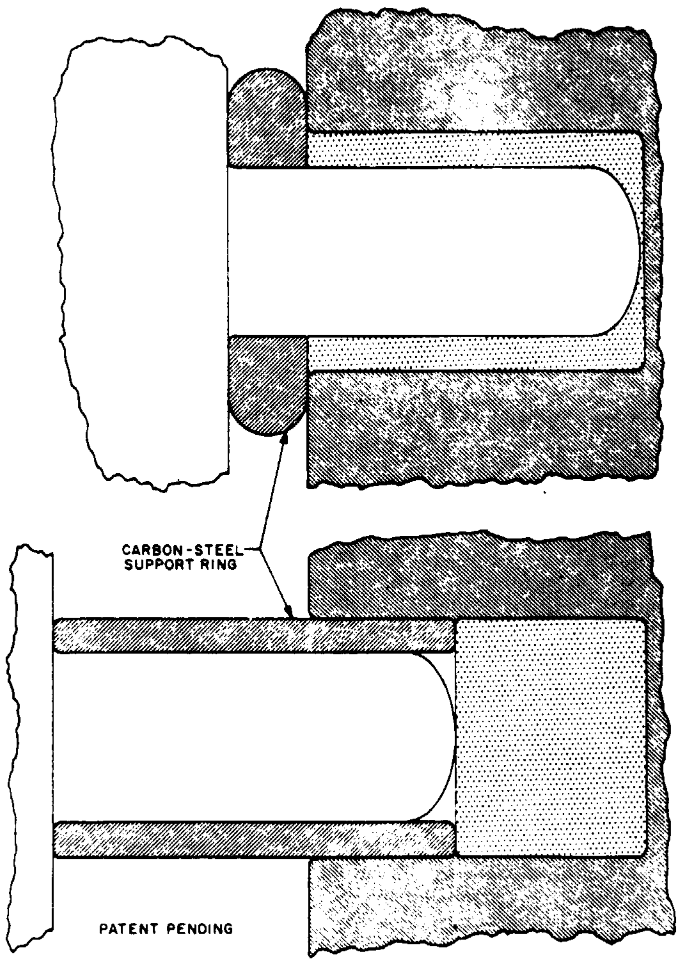

Figure 8. Tooling Used for the Carbon-Steel Support Ring Technique[29]

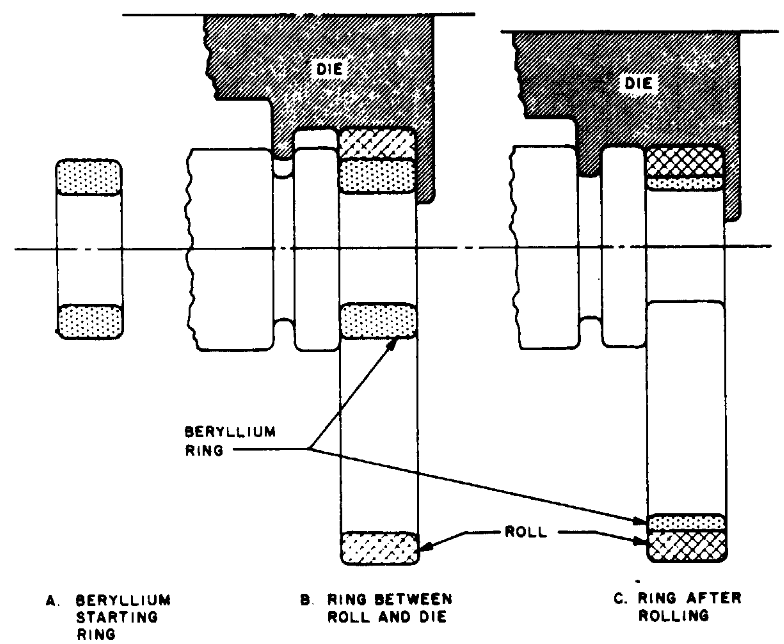

Figure 9. Ring-Rolling Tooling Technique Used in Program at Ladish[29]

to forging preforms by the four methods. It can be seen that for small quantities of parts of rather complex shape, the slip cast and sinter fabrication technique is most economical. However, when large quantities of parts are involved, the cold press and sinter or the chip compaction and sinter techniques are more economical.

Work at the Brush Beryllium Company[31] has been concerned with developing the technology for forging beryllium aircraft and missile shapes from unclad beryllium preforms and billets. The part chosen for study, an aircraft bracket, is somewhat more sophisticated in design than the shapes forged in the Ladish program. The general design is shown in Figure 10. The variations in shapes make the production of these parts a real challenge for the industry. The summary report[31] indicates that the first two phases of a three-phase program have been completed. The study was made with unclad commercial hot-pressed S-100-B, S-200-B, and I-400 grades of beryllium and also pressureless sintered preforms of the same three grades. The part was produced by press forging at 1375°F using a two-step operation with machining between the block and the finish forging steps.

Tensile properties at room temperature and at 800°F were determined at various positions on brackets forged from the three commercial grades of beryllium

4. Sheet Forming Operations

Forming beryllium sheet and plate into shapes is generally carried out in the bare condition using preheat temperatures from 800° to 1500°F.[19] Hot-pressed material usually requires a lower forming temperature than cross-rolled sheet. It can be formed below 1000°F when heated dies are used. Sheet and plate less than 0.5 inch thick can be bent, deep drawn, and wrapped.

Beryllium sheet, plate, and strip have been formed into angles, channels, Z-sections, corrugations, and other configurations.[7] In spite of the fact that Figure 11 shows higher elongation values in the range of 700° to 800°F, successful forming usually is limited to temperatures between 1000° and 1400°F.[19] Spinning and drawing operations also are carried out in this temperature range.

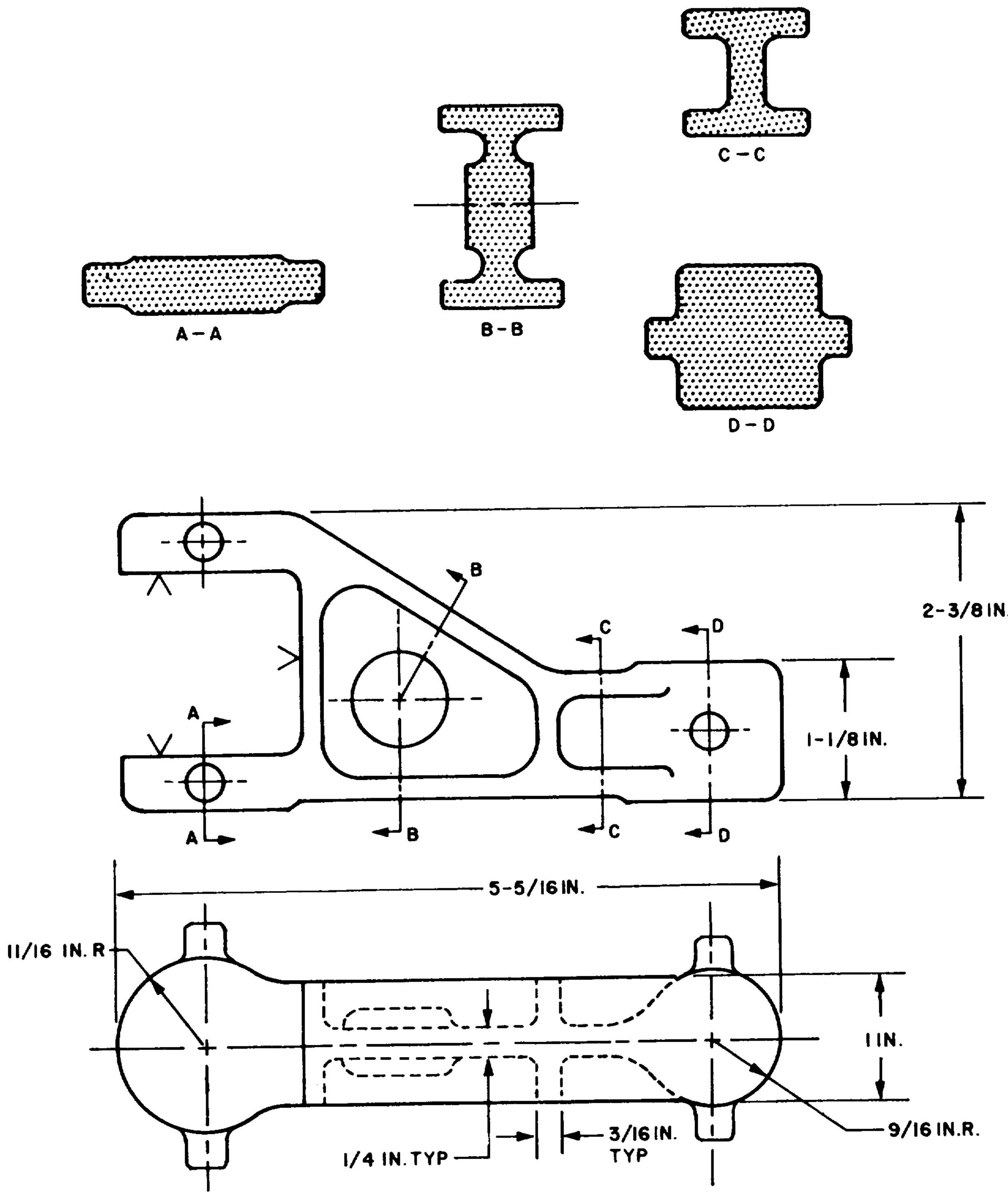

Figure 10. Aircraft Bracket (Prior to the Addition of Forging Draft and Taper Per Design Criteria)[31]

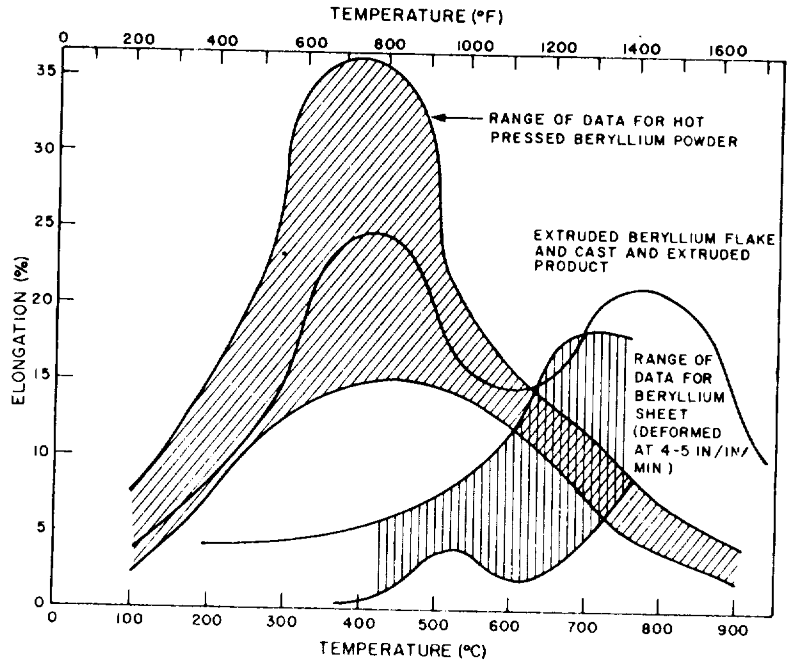

Figure 11. Deformation Characteristics for Several Types of Beryllium Metal Products[26]

The temperature of forming often determines the sharpness of a bend that can be made with beryllium sheet.[32] This is illustrated for the mechanical brake forming of 0.060 inch thick low-oxide sheet at 4.5 inches per minute. At 1400°F, crack-free 90-degree bends can be made over a 6t (0.360 inch diameter) radius. At 1250°F, the radius of the bend must be increased to 8t (0.480 inch), while at 1000°F, the bend radius must be 10t (0.600 inch) to bend the sheet 90 degrees without cracking.

Hot pressed metal or wrought sheet can be formed either by reduction or by bending methods. A reduction technique is shear forming, also known as hydrospinning, shear forging, and flow turning. This method provides an accurate means of forming sheet metal into conical, contoured, or cylindrical shapes by displacing metal parallel to the center line of the part being formed.

a. Shear Forming

Shear forming consists of spinning a large, rather thick blank of beryllium over a mandrel by means of a lathe and one or two power-driven shear forming rolls.[33] The metal is displaced by a shearing action, and the blank is reduced appreciably in thickness.

Limited success resulted when the blank was heated to approximately 1000°F and the mandrel to approximately 600°F. Even the best truncated-cone parts that have been formed to date have contained microcracks on the external surfaces.[33] A considerable amount of additional development work will be needed to establish optimum forming temperatures and deformations.

The maximum reduction in thickness which can be accomplished in shear forming cones and tubes can be predicted from reduction in area values obtained in uniaxial tension tests. Materials characterized by reduction in area values of 50 percent or more will ordinarily withstand shear forming reductions of 80 percent in thickness without cracking. For less ductile materials, the maximum permissible reduction in shear forming is directly related to their tensile reduction in area values. This generalization can be used for choosing shear forming temperatures.

A shear-formed bowl of beryllium is illustrated,[19] which was formed from a hot-pressed disk 12 inches diameter by 0.25 inch thick. The mandrel was a section of a cone, 5 inches on the small diameter, 12 inches on the large diameter, and 4 inches high with a 60-degree included angle. Heat was applied externally by torches. Tensile strengths of 70,000 psi and yield strengths of 55,000 psi indicate that a substantial amount of cold work went into forming this shape. Although truncated cones have been successfully shear formed, the forming of hollow hemispheres by this method has not yet been successful.[19]

b. Roll Forming

Although it has been found possible to cold-roll form beryllium sheet to plastic strains that approach the tensile strain recorded in tensile testing the sheet, the beginning of failure caused by small geometrical and material differences from sheet to sheet make such cold-straining operations economically impractical.[25]

Weismantel and Kopelman[25] have reported that thin beryllium sheet, 0.040 to 0.125 inch thick, may readily be deformed by bending operations at 1200° to 1400°F. Since roll forming is essentially a continuous bending operation, beryllium is readily formed by this technique.

Progressive roll bending of 0.060 inch thick beryllium sheet is a means of obtaining sharper bends than are possible with some other methods.[32] Using a strain rate of 2 percent per pass at 950°F, it was found possible to obtain satisfactory 90-degree bends with a 3t (0.180 inch) bend radius. At 850°F, at the same strain rate and bend radius, cracking was encountered at approximately 50 degrees. These data also illustrate the effect of temperature on the bending of beryllium by roll forming.

c. Explosive Forming

A liquid or gas is used to transmit the shock waves generated by the explosive charge in explosive forming. These shock waves deform the material into a properly shaped die cavity which ordinarily is evacuated. Attempts to form beryllium sheet into a 3 inch diameter die cavity, 0.30 inch in height, were not successful. In all cases, the beryllium shattered even though the blanks were heated to 600° and 775°F.[33] Perhaps the use of higher temperatures would permit a limited amount of forming to be done explosively.

d. Creep Forming

Forming of beryllium is generally more successful with lower deformation rates than with higher rates.[25] The lower the rate of deformation, the greater the total deformation obtained without fracture.[32] This can be illustrated by the fact that it was found possible in creep bending at 1350°F at a strain rate of 0.001 to 0.005 inch per inch per minute to obtain crack-free 90-degree bends in 0.060 inch low oxide sheet over a bend radius of 4t (0.240 inch). At a rate of 4.5 inches per minute in mechanical brake forming, the 0.060 inch thick sheet was limited to a 6t (0.360 inch) bend radius to obtain crack-free bends.

One recent practical application of creep forming of beryllium sheet was the production of the two 180-degree beryllium skin sections by Brush Beryllium Company for North American Aviation, Columbus Division, for an experimental structural test Minuteman guidance and control body section.[34] The body section is a truncated cone, 36 inches high, having a major diameter of 36 inches and a minor diameter of 32 inches. The skin sections, 0.060 inch thick, were creep formed at 1250°F in 3 or 4 steps using stainless clad carbon steel forming dies.[34] This assembled component is shown in Figure 12.

5. Drawing of Fine Beryllium Wire

Fine wire has been produced at Brush Beryllium Company[8, 35, 36, 37, 38] and at The Beryllium Corporation[39] from beryllium metal. Gross[36] described the drawing of wire from vacuum hot-pressed beryllium block. The stock for drawing was fabricated by extruding the hot-pressed beryllium at 850°F, with a 6:1 reduction ratio, to 0.250 inch diameter rod. The wire was drawn at 800°F through tungsten-carbide dies. The beryllium was heated to 850°F; the die box was heated by a gas burner to 700°F. Dies with 12.5-degree full-entry angles and zero-bearing length were used. The draw stock was pointed by etching and coated with a solid-film lubricant, preferably a graphite-molybdenum disulfide mixture with a phenolic resin binder. The stock was annealed and cleaned prior to coating. The production drafting cycle consisted of three drawing passes, each reducing the area by 25 percent. Process annealing was performed at 1450° to 1500°F for 30 minutes, followed by air cooling. Beryllium wire down to 0.010-inch diameter was commercially available in 1960.

Later work with zone-refined beryllium crystals of both thermally and electorlytically reduced metal was performed by somewhat similar standard wire drawing and swaging techniques.[36] The zone-refined crystals were converted to polycrystalline metal by a combination of deformation and heat treatment. Deformation was accomplished at 450°C (842°F) generally both by swaging and rod-drawing techniques, although swaging appeared to be the more successful method. The beryllium was jacketed in steel while being deformed.

Nonmetallic inclusions, believed to be beryllium oxide, were present in some of the zone-refined metal. Their presence appeared to cause catastrophic failure of the wire during drawing.

Generally, the wire fabricated from zone-refined beryllium had the same metallurgical characteristics as comparable commercially pure wire. At high wire drawing reductions and also when subsequently annealed, the as-drawn, zone-refined wire was only approximately half as strong as the commercially pure wire.[8] The ductility in the drawn condition was approximately the same for both types of wire; however, when annealed, the zone-refined wire was about three times as ductile as the annealed commercially pure wire. As might be expected, the zone-refined wire showed a surprising capacity for grain growth and suffered extensive reorientation during recrystallization annealing.

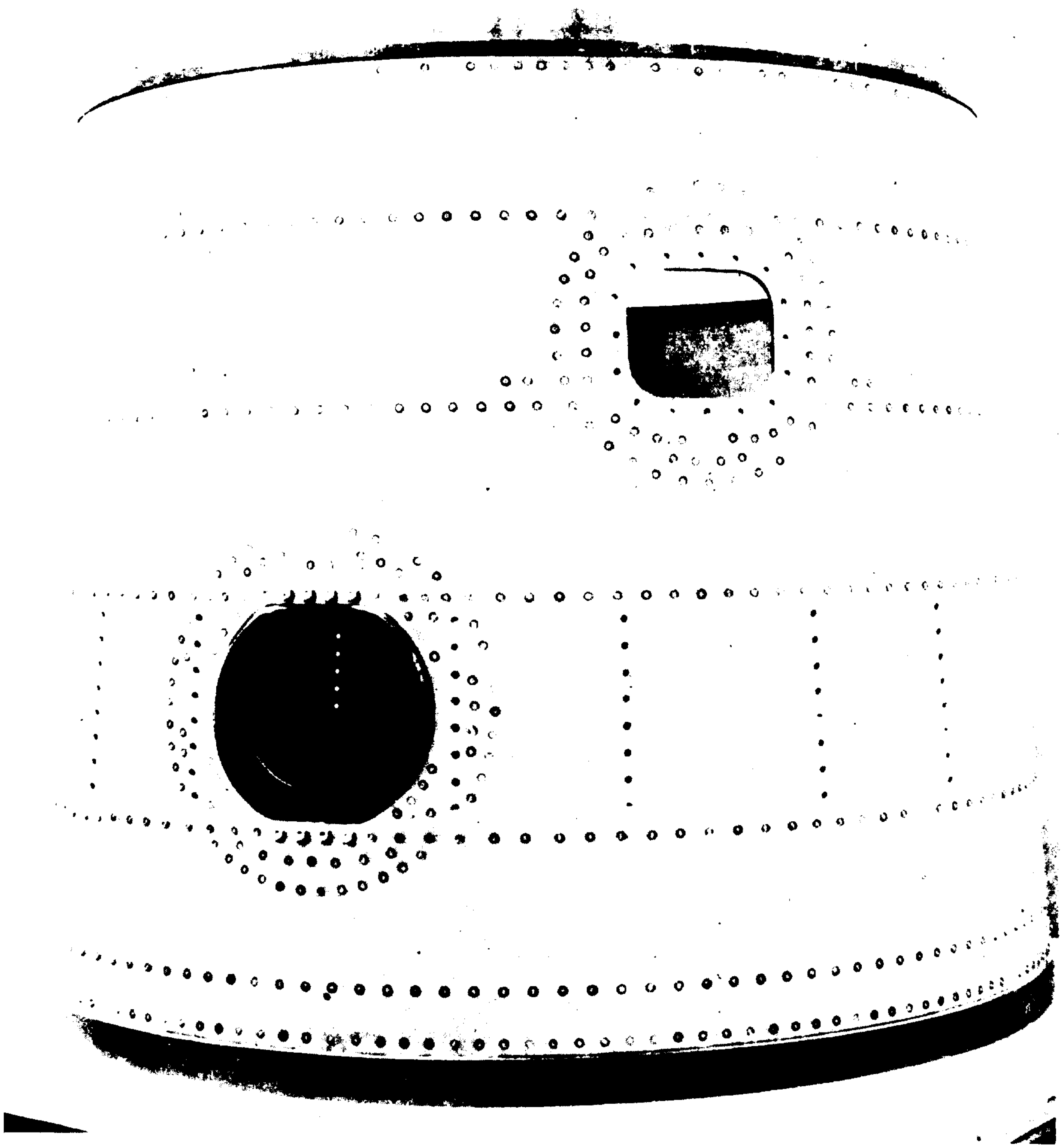

Figure 12. Experimental Minuteman Guidance and Control Body Section Fabricated from Beryllium Sheet by Brush Beryllium Company for North American Aviation, Columbus Division[34]

Later work by Murphy and O'Rourke[38] directed at developing a process for drawing ultrafine wire (down to 0.001 inch diameter) indicated that commercially pure beryllium wire (s-200-B grade), as drawn to 0.00477 inch diameter, could not be further drawn by cladding the annealed* wire in a steel tube and then drawing. However, using conventional warm drawing techniques, consisting of reducing the bare wire at 700° to 800°F in 10 percent reductions per pass at speeds of 5 to 15 feet per minute, the wire could be successfully drawn through diamond dies. The standard molybdenum disulfide lubrication system (Acheson Dag 206) was used with the lubricant thinned 2:1 with water. The dies were heated at 700°F for this work. Wires drawn to 0.001848 inch diameter were obtained in relatively long lengths. Drawing difficulties were found to increase for smaller diameters. However, four lengths, each over 25 feet long, were produced in the 0.001578 and 0.001497 inch size range.

Typical mechanical properties obtained on drawn wire[38] less than 0.006 inch in diameter are listed in Table XI. It can be seen that the highest tensile yield strength and ultimate tensile strength were produced in wire of 0.001848 inch diameter that had been reduced since last annealed at 0.062 inch diameter by a reduction ratio of 1120:1 (approximately 94.3 percent reduction in area). Additional reductions produced lower strengths. The elongation values generally decreased directly with the percent reduction after annealing. An exception to this is the wire drawn through the 0.00303 inch diameter die. This wire was slightly more ductile and showed slightly lower ultimate tensile strength than that drawn through a 0.002164-inch diameter die. The reason for this apparent anomaly is not known.

In a program being conducted at the Beryllium Corporation,[39] four basic forms of beryllium, high purity cast metal, hot pressed low oxide block, hot pressed select standard grade block, and vacuum, hot pressed Pechiney SR grade powder were extruded to 0.375 inch diameter rod. The select standard grade beryllium rod was drawn at speeds of 13 feet per minute after heating at 800° to 850°F using tungsten-carbide dies with entrance angles of 12.5 degrees. The dies were heated to approximately 700°F. Drawing reductions of 12.5 and 25.0 percent per pass were equally satisfactory for cumulative reductions of approximately 55.0 percent between anneals. Specimens were process annealed for 30 minutes at 1400° to 1450°F. The beryllium was drawn from 0.375 to 0.075 inch on a mechanical draw bench

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*Annealed by heating at 1500°F for ¼ hour in argon and air cooling.

Table XI. Typical Mechanical Properties Determined on Beryllium Ultrafine Wire Reduced Various Percentages After Annealing at 0.062-Inch Diameter[38]

Drawn Diameter* (in.)	Reduction Ratio From Last Anneal	Room-Temperature Tensile Properties		
		Ultimate Strength** (psi)	Yield Strength*** (psi)	Elongation† (%)
0.00588	111 to 1	173,200	135,300	1.68
0.00303	418 to 1	172,500	138,100	1.71
0.002164	820 to 1	177,400	139,700	1.47
0.001848	1120 to 1	203,300	153,500	1.29
0.001753	1250 to 1	176,900	140,500	1.03
0.001663	1440 to 1	157,900	††	0.53
0.001497	1720 to 1	136,900	††	0.32

* The drawn diameter was considered equal to the specified die diameter and was used in the calculation of the tensile strength, both yield and ultimate.

** Ultimate strength was computed by dividing the maximum load by the area corresponding to the specified die diameter.

*** Yield strength was computed by dividing the yield load at 0.2 percent offset by the area corresponding to the specified die diameter.

† Elongation was graphically measured on the load-deformation curve obtained with the Instron tester.

†† Some of the wires used for the average values fractured prior to reaching 0.2 percent offset for yield determination.

and then drawn on a capstan type drawing machine to finer diameters. Most satisfactory lubrication was obtained with commercial lubricant containing colloidal MoS_2 in water and MoS_2 plus graphite in a phenolic resin solution. However, galling, which resulted in wire breakage, was a continuing problem. The use of nickel cladding on the 0.099-inch diameter beryllium wire eliminated galling and facilitated the drawing of this wire to 0.005 inch diameter. Continuous lengths of up to 500 feet of 0.005-inch diameter wire were obtained by this technique using the MoS_2 base lubricants. The use of the cladding also eliminated some of the anneals and it was found that wire could be drawn from 0.375 to 0.005 inch diameter with two intermediate process anneals, one at 0.300 and the other at 0.068 inch diameter. Wire with an ultimate strength of 174.600 psi, proportional limit of 69,000 psi, and elongation in 10-inch gage length of 1.74 percent was produced by these techniques. This program is continuing.

If further information on beryllium forming is desired, see TM X-53453, The Fabrication of Beryllium - Volume II: Forming Techniques for Beryllium Alloys.

SECTION V. POWDER METALLURGY METHODS

Commercially pure beryllium is a powder metallurgy product made by vacuum hot pressing powder produced from vacuum melted beryllium ingots. In this section, it is planned to discuss methods of producing rather intricate shapes of beryllium by powder metallurgy methods and not the production of hot-pressed beryllium block. Essentially, two methods are available for producing shapes from beryllium powder - slip casting and isostatic pressing. Both techniques are approaching commercial application, and in fact some forging billets of rather intricate shape have been produced by both methods. Both techniques have been used extensively in the ceramic industry for years.

1. Isostatic Pressing

Isostatic pressing is the simultaneous and equal application of pressure from all directions to a powdered material contained in a tightly sealed flexible container.[40] The pressure is transmitted by either a gas or a liquid. If the pressure medium is a gas, the term isostatic pressing generally is used; if the pressure medium is a liquid, the term is hydrostatic pressing. However, the term isostatic pressing often refers to both gaseous and liquid media. Most often, the method is used at or near room temperature.

The principal advantages claimed for isostatic pressing are the following: [40]

Uniform strength in all directions regardless of size

Close control dimensions and surface finish

Production of shapes that are impossible by other methods, e.g., longer length per diameter ratios

Better homogeneity; fewer voids and air pockets and lower internal stresses

Exotic, hazardous, and expensive materials can be processed with minimum scrap

Lower die cost through use of rubber or plastic molds

Lower equipment and installation cost.

Considerable savings in materials and machining as well as less scrap with a greater degree of safety can be achieved in producing beryllium parts by isostatic pressing.

There is comparatively little background for the isostatic pressing process in the field of metal powders. For specific applications, it is recommended that an evaluation program be set up to determine optimum operating parameters. It is of prime importance that the powder flows properly, filling the mold to a uniform density and without bridging. Up to 5 percent moisture in the powder is said to produce higher densities. Sometimes vibration is used to assist in filling the mold, in increasing density, and in reducing the compression ratio. The powder may also be preformed, placed in the mold, and pressed.

After the mold has been properly filled with powder, it must be sealed airtight. Sometimes the air must be evacuated from the mold to assist in compacting the powder. For metal powders, compacting pressures ranging from 30,000 to 100,000 psi are used, with 30,000 to 50,000 psi being a common range.

Tatman[33] reports that complicated shapes have been produced from beryllium powder by isostatic pressing methods. The plastic mold was made by dipping an oversize aluminum pattern into a liquid plastic followed by proper curing of the plastic. After the flexible mold was stripped from the pattern, it was filled with beryllium powder, using slight vibration, and then sealed. Then the mold and compressed powder were compressed in a liquid filled pressure vessel at pressures up to 50,000 psi to form a preform having a density of approximately 1.4 grams per cubic centimeter. Such preforms can readily be handled and even machined if necessary.

The preforms are sintered in vacuum at 1150°F to achieve full density. Parts produced successfully by this technique have included small-scale, closed-end cylindrical, and truncated cones. Mechanical properties of such parts are comparable to those obtained by forging or extrusion methods. Experimental tensile data obtained at three locations in a hemispherical closed-end cylinder are shown in Table XII. These properties appear rather uniform in comparison with those of parts wrought by other techniques.

The cost of the pressure chamber for large parts would probably restrict the use of this technique to production quantities where amortization charges per part are relatively small.

Table XII. Room Temperature Mechanical Properties at Various Locations in an Isostatically Pressed Beryllium Hemispherical Closed-End Cylinder[33]

Specimen Location	Ultimate Tensile Strength (psi)	Tensile Yield Strength (psi)	Elongation (%)
Hemisphere section parallel to cylinder axis*	53,100	49,200	0.64
Hemisphere section perpendicular to cylinder axis	58,200	49,300	2.34
Cylindrical section parallel to axis	52,900	47,800	1.19

*Microtest specimen, $^3/_4$ inch long.

2. Slip Casting

In slip casting, fine powders suspended in a liquid are caused to deposit in a suitable shape or preform.[41] Usually the suspended material is deposited on the surfaces of a porous mold or mandrel by capillary action. This results in a free-standing shape which then is parted from the mold.

The principal advantage of slip casting is the ability to produce shapes from materials which probably could not be produced, or could be produced only with great difficulty, by machining or other processing methods.[42] The principal disadvantage of the slip casting process is the extreme fragility in the green state. Strength and other desirable properties can be developed only by sintering. Because of the low density of the slip casting, considerable shrinkage may cause distortion and cracking. Precise control of particle size distribution is essential for dimensional reproducibility. This control of particle size is difficult, especially with the fine grained powders needed to successfully operate the process.

Figure 13 is an outline of the slip casting process.[41] The metal powder and the vehicle are usually combined with an additive to

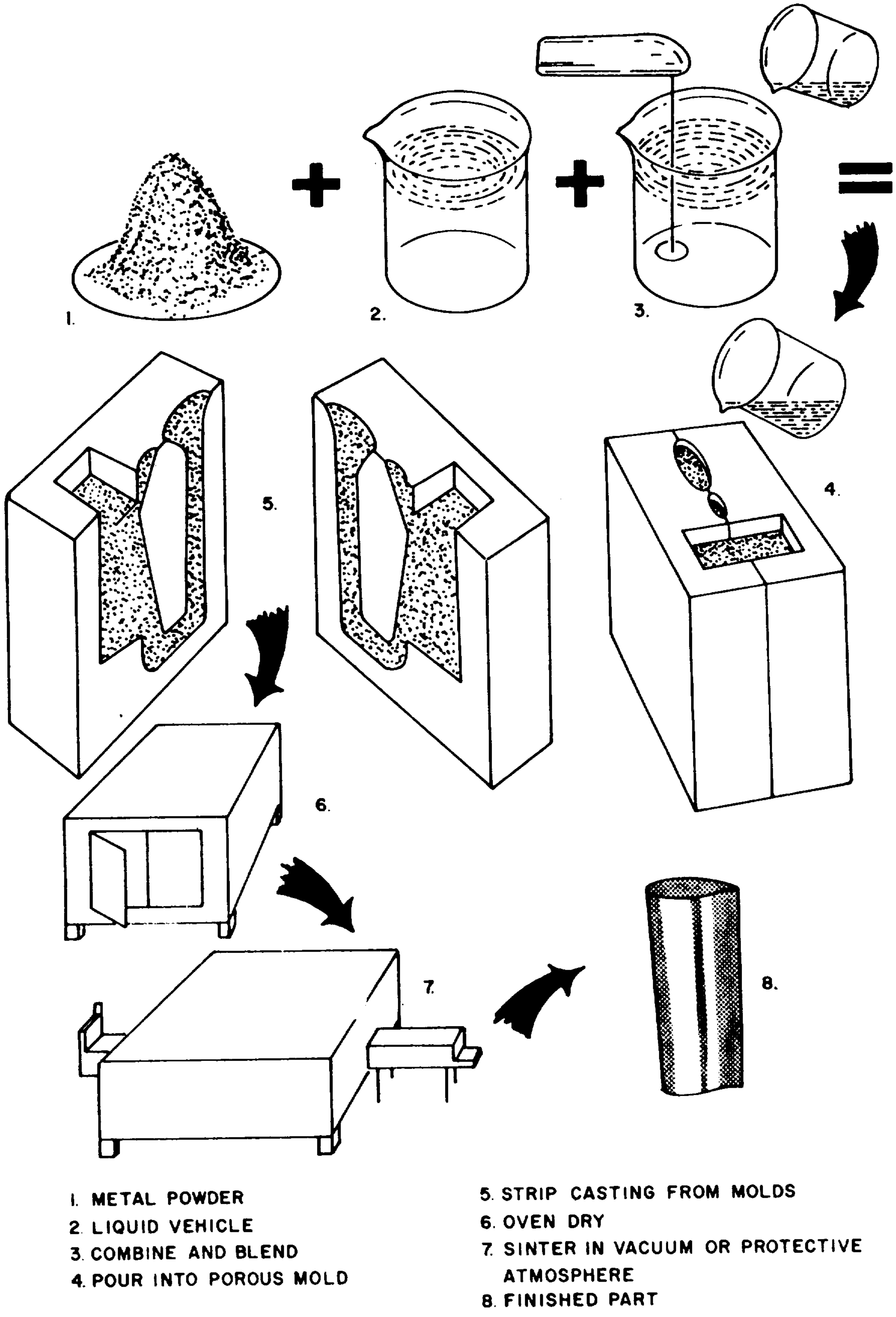

Figure 13. Outline of Slip-Casting Process[41]

maintain a stable suspension, blended, and then poured into the split plaster mold. The casting is removed from the mold, oven dried, and then sintered in vacuum or inert atmosphere.

It is known that gimbals have been cast by the Brush Beryllium Company under contract to NASA, Huntsville, Alabama.[43] These gimbals, weighing approximately 3.5 pounds each, were vacuum sintered at 1230° to 1235°F for 5 hours and attained approximately 95 percent of the theoretical density of beryllium. Shrinkage during sintering normally amounted to approximately 15 percent. Other details are contained in the report which was not available to the author.

Work was recently begun at the General Electric Advanced Engine Technology Department at Cincinnati, Ohio, to develop and evaluate techniques to slip cast consistently reproducible, reliable, and sound structural parts of U-700, In-100, X40, A286, beryllium, and TZM molybdenum.[44] The desired mechanical properties of such parts are to be comparable to wrought or cast materials produced by more conventional manufacturing methods. No work has yet been reported on slip casting beryllium on the program although the experimental powders recently became available.

If further information on beryllium forming is desired, see TM X-53453, The Fabrication of Beryllium - Volume II: Forming Techniques for Beryllium Alloys.

SECTION VI. MACHINING BERYLLIUM

The machinability of hot-pressed beryllium block compares favorably with that of heat-treated aluminum castings and cast iron although beryllium is more brittle and abrasive.[7,45] Extruded beryllium appears to offer better machinability, at faster rates, to closer tolerances, with improved surface finishes. Coarse-grained cast beryllium requires more care in handling than fine-grained hot-pressed beryllium, but in other respects they machine essentially alike.

Machined surfaces of beryllium may have a scuffed appearance, caused, in part, by pieces adhering to the built-up edge which periodically separates from the tool and mars the surface. The use of increased rake angle and shallow depths of cut improves surface finishes.

Standard tools (preferably carbide tipped), jigs, and fixtures, such as are used on aluminum or steel, can be used on beryllium for turning, boring, milling, drilling, sawing, grinding, and abrasive cutting.

Because of the cost of beryllium (approximately six times that of silver), care must be taken to secure clean, uncontaminated chips suitable for direct reprocessing. Even slightly contaminated chips may be devalued up to 75 percent as compared with clean chips. If the machining is accomplished dry, the chip is of such quality that it may be converted directly into powder and recycled for preparation of new hot-pressed billets.

Until the last several years, most of the shapes made from beryllium metal were produced by various machining operations. The high price of beryllium made it very expensive to produce beryllium parts and resulted in the production of rather large quantities of scrap. In recent years, much effort has gone into studying methods of shaping beryllium by means other than machining. These have included powder metallurgy methods such as slip casting and isostatic pressing as well as metalworking methods including extrusion, press foring, and bar rolling. In addition, machining of hot-pressed block by unusual trepanning and parting operations have also tended to reduce the quantity of chips produced. Thus, solid beryllium trepanned from the core of a rather large shape could be used to produce a smaller shape with correspondingly fewer chips as scrap.

1. Drilling

Drilling holes in beryllium to depths less than five times the diameter is considered conventional; depth exceeding five times the diameter is designated as deep-hole drilling.[46] The main difficulties in drilling beryllium are tool wear and avoiding laminar breakout or spalling as the drill emerges from the far side of the hole.[7] Tool wear problems can be solved by using solid carbide or carbide tipped drills. The breakout problem is eliminated by using a backup plate or block of beryllium or steel. High-speed steel drills may be used for limited applications if carbide drills are not available.

Fast spiral drills are preferable to standard drills and drill point angles of 90 degrees with webs 0.015 or 0.020 inch thick help in producing satisfactory cutting angles. A drill configuration recommended by one fabricator[7] is shown in Figure 14. A narrow land is formed by the primary and secondary clearance angles in this configuration which is very similar to that employed on milling cutters. This provides additional support to the cutting edge while supplying sufficient relief. It was found that several hundred holes can be drilled in relatively thin material without regrinding the drill. Drilling can be done dry, and a cutting speed of 70 to 100 surface feet per minute has given best results.

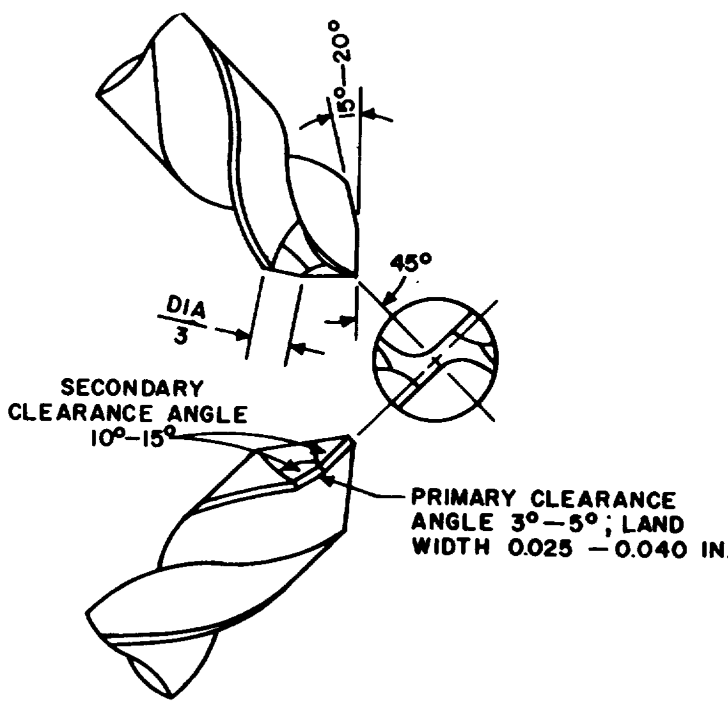

Figure 14 Recommended Drill Configuration for Drilling Beryllium[7]

Some beryllium fabricators are successfully drilling holes as small as 0.002 inch in diameter. Holes under 0.065 inch in diameter are no longer difficult to drill. Following are recommended speeds and feeds for drills of various diameters:

Drill Size (in.)	Speed (fpm)	Feed (ipr)
Under 1/8	70 - 100	0.001 - 0.002
1/4	70 - 100	0.002 - 0.004
1/2	70 - 100	0.005
>1/2	70 - 100	0.005 - 0.007

Reaming a drilled hole produces accurate dimensions and a smooth finish. The amount of stock to be left for removal after drilling depends on the finish required, the depth of the hole, and the chip capacity of the reamer. Following is the recommended stock allowance in reaming:

Diameter of Hole (in.)	Stock Allowance (in.)
1/4	0.004
1/2	0.007
1-1/2	0.010

An allowance of 0.001 to 0.003 inch is common practice for hand-reaming operations. The optimum speed of reaming is controlled by the rigidity of the setup and by the tolerance and finish required. Excessive speed can cause chatter which is harmful to both reamer and finish. Suitable reaming speeds are approximately two-thirds of those listed for drilling.

A recent development[47] in the drilling of beryllium is the use of the Tornetic drilling system produced by Dyna Systems, Inc., Torrance, California. The system employs an analog computer to regulate torque and feed rates. Using a variation of the spade-type carbide drill with special angles instead of the modified split-point carbide drill previously described, this method of drilling eliminates breakout without resorting to the added expense of backup procedures. A patent application has been filed on the new drill configuration. The spade-type drills are made by Metal Removal Company, Chicago, Illinois. Using these new techniques, it is possible, for example, to drill a 0.1875-inch diameter hole through 0.125-inch thick beryllium sheet in less than 30 seconds.[47] The same operation reportedly took approximately 5 minutes by older methods.

Figure 15 shows the drill configuration for a recently developed burr-tooth drill.[48] The drill is solid carbide and has two flutes. There are five burr teeth on each side of the drill as shown in Figure 15. The main tooth has an 8- to 10-degree clearance angle while the remaining teeth have clearance angles of 5 degrees. The ground angle on the drill is not flat but has a small radius, being 0.140 inch for the 0.1875-inch diameter drill shown in Figure 15.

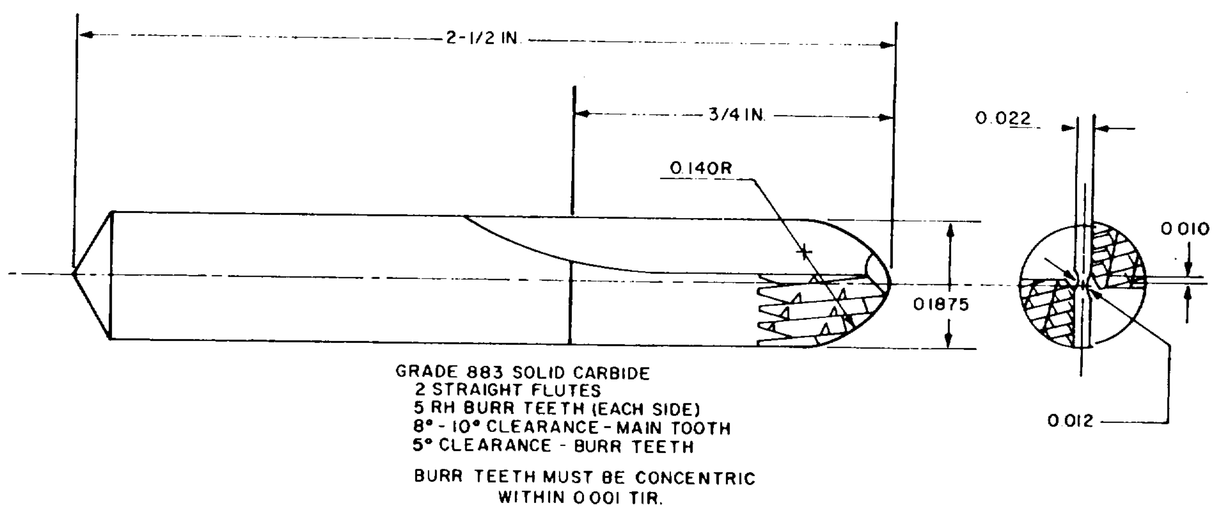

Figure 15. Drill Configuration for Recently Developed Burr-Tooth Drill[48]

The Tornetic drilling unit drills holes 0.002 inch undersize[47] in a 0.160-inch thick beryllium shell of the spacer for the Minuteman missiles being produced by The Brush Beryllium Company. The remaining 0.002 inch is then removed when the spacers are etched chemically after machining to remove the effect of the residual stresses produced during machining and drilling.

2. Deep-Hole Drilling

Deep-hole drilling (in which the depth of the hole is greater than five times the diameter) is difficult and calls for specialized techniques including the use of cutting fluids under pressures up to 3000 psi and special oil-hole or rifle drills. These rather high pressures require oil pumps as large as 50 hp. Holes 0.250 inch in diameter have been drilled up to 32 inches deep.[45]

One difficulty in deep-hole drilling is that as the heat of cutting accumulates in the drill and in the work, the drill may expand more than the hole, eventually causing the shank to rub against the wall. This in turn causes more heat and binding until seizure and drill failure occur. With certain modifications in drill and toolholder design, deep holes can be successfully produced using either a standard drill press or a deep-hole drilling machine. Pieces too large to rotate in a drilling machine can be drilled in a modified engine lathe.

The standard drill design for deep-hole drilling is a two-flute oil-hole drill, carbide tipped, with its point ground to a 90-degree included angle. The drill shank should be undercut 0.010 inch on the diameter behind the carbide tip, which should back taper 0.004 inch per inch. The primary clearance angle should be increased to approximately 6 degrees.

Special toolholders are used in conjunction with the above drill design to help minimize tool breakage. Essentially, they incorporate a spring-loaded clutch which breaks free in case the drill is overloaded, thus permitting the drill socket to rotate freely in the toolholder.

Single-fluted, carbide-tipped rifle drills also are used in deep-hole drilling.[49] Such a drill is shown in Figure 16. The shank is a seamless steel tube with a slightly smaller diameter than the tip. The tube is brazed to the tip. One side of the tube is depressed to form a "V" groove which extends the entire length of the shank to the drill point. The groove is continued to the drill point by grinding off approximately one-third of the cross-sectional area of the tip. Two holes, approximately 0.03125 inch in diameter, are drilled longitudinally through the tip just below each outer corner of the "V" to direct the coolant to the cutting area. The "V" groove permits the coolant laden with chips to leave the cutting site. Longitudinal clearance is present along the tool body to reduce friction and to allow coolant to flow around the tip and into the "V" groove.

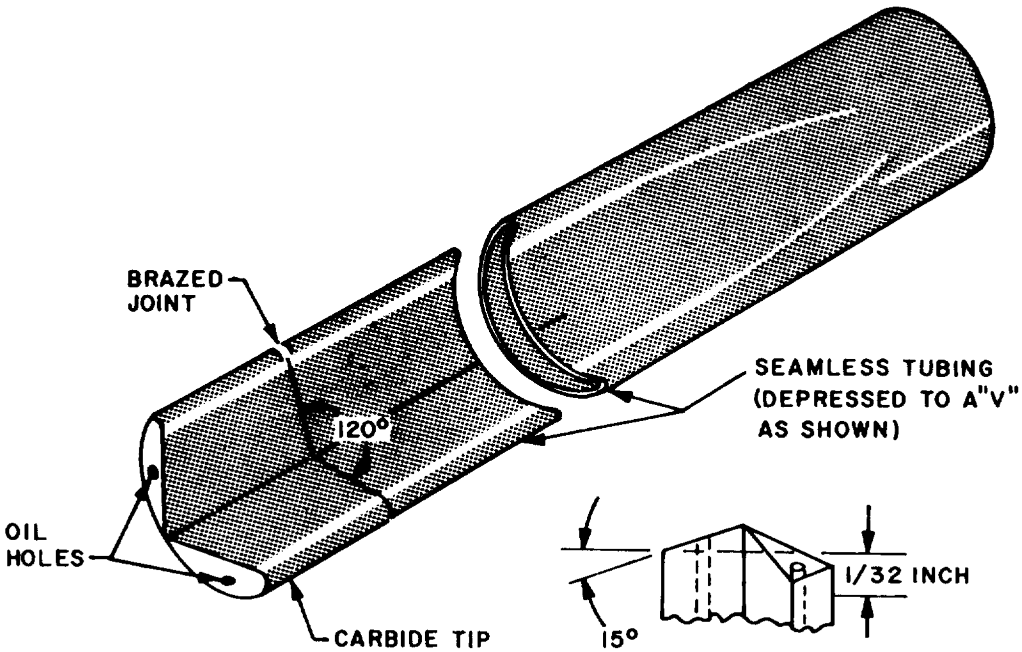

Figure 16. Carbide-Tipped Rifle Drill[49]

The drill face is ground so that a line along the cutting edge in the "V" makes a 15-degree angle with the cross section of the drill and with any line on the face perpendicular to the axis of the drill. Thus, the face recedes from the point and from the cutting edge of the drill on a compound angle which forms a 15-degree side-cutting angle and a 15-degree end-cutting angle.[49]

A slight clearance is ground on the point to prevent shearing as it enters the work. A clearance also is ground around the coolant holes on the lower side of the drill face to allow a larger space for flushing chips from the cutting site. This clearance is bounded by a line passing slightly off center between the coolant holes, the lower edge of the "V" groove, and the periphery of the drill.

Following are recommendations for speed, feed, and depth of cut for the deep-hole drilling of beryllium:[49]

Diameter (in.)	Depth (ft)	Speed (fpm)	Feed (ipr)
1/8	2 - 3	70 - 100	0.0004

The drilling speed, 70 to 100 fpm, using carbide drills applies for both deep and shallow holes. In deep-hole drilling, the feed rate is reduced. For holes 2 or 3 feet deep, the feed rate should be 0.0004 inch per revolution for a 0.125-inch diameter drill. The rate is increased proportionately with larger diameters or reduced depths. The coolant is commercial grade kerosene at a minimum pressure of 200 psi. Much higher pressures may be used on rifle drills.

3. Electrical Discharge Machining

The drilling of small holes in beryllium parts often presents problems which are difficult or cannot be solved by mechanical drilling techniques.[50] Since beryllium is brittle, a drill will often chip the edges of a hole. The hardness of the metal makes it possible to deflect a small drill off its course even when supersensitive techniques, commonly used to drill aluminum, are used.

For these and other reasons, drilling and machining by electric spark is coming into wide use among producers and fabricators of beryllium and other exotic metals.[46] In this process, the work is the anode, and a spark is created between it and the cathode. A pulsating direct current is used with a dielectric, such as light oil, which is a moderate conductor or even a poor conductor of electricity.

During machining, a rapid succession of sparks of high current density (10^6 amps per square inch) creates a kind of tunnel in the dielectric (light oil), which controls or resists the expansion of the resulting gas bubbles and confines the arc to a predetermined diameter. The frequency (or rate of pulsation) of the direct current consists of tens or hundreds of thousands of sparks per second, each of which lasts approximately 30 microseconds. The arcing process rapidly erodes away the metal.

In one application,[50] a hole 0.028 inch in diameter was drilled in beryllium using a beryllium copper tube having an outside diameter of 0.026 inch and an inside diameter of 0.015 inch. Thus, the cutting zone could be flushed by drawing dielectric fluid up through the electrode. Even in this small diameter, the electrode performed a trepanning operation in that a small slug of beryllium was left inside the tubular electrode when the hole had been completed. The equipment used for this application was the Agietron Model 1.5 which is a high precision bench unit designed for small work.

In electroerosion, lower erosion rates produce smoother finishes.[50] Therefore, small precise holes, which must be extremely accurate, are always produced at very low feed rates.

Advantages claimed for electrical discharge machining include the following:

It succeeds in producing complex or irregular forms of cavities (star-shape holes, hexagonal, and other regular or intricate configurations) of extremely small or very large diameters that cannot be machined by other currently used techniques.

It results in a saving of material, hence, has a cost advantage on specialized applications.

4. Lathe Operations

Lathe operations are used on beryllium to produce turned surfaces and external threads.[49] Speeds and feeds similar to those used for cast iron are suitable for machining beryllium. It is important, however, that the actual cutting speed does not exceed the capacity of the exhaust system and method of collecting chips. Because of this factor, lower speeds usually are necessary for clean chip salvage and efficient dust disposal.

Threading is done in a lathe with a single-point tool instead of by means of dies or chasers.[31] When dies are used, beryllium may spall off in small pieces which would crowd into the die, tearing the threads produced and causing the die to wear excessively.

Carbide tipped single point tools are recommended for machining beryllium.[49] High speed steel tools can be used but are normally not used because of rapid tool wear. Best results are obtained with carbide grade C-1 or equivalent for roughing the interrupted cuts, and with carbide grade C-2 for finishing. These grades give longer tool life.

Beryllium tends to chip or break off when the tool leaves the cut.[49] This spalling may be minimized by chamfering both ends of the work to the required finished diameter before turning. An alternative method is to finish turn one end for a short distance, reverse the ends, and then finish turn the remainder. In both instances, finishing cuts not exceeding 0.015 inch deep should be taken. When turning beryllium on centers, the use of live centers is recommended because beryllium is highly abrasive to all tooling.

Tool design recommended for turning and forming of beryllium on the lathe are given in Table XIII. Proper rake angles promote free cutting and maximum tool life.[46] Excessive rake angles must be avoided since tool breakage, which decreases the value of beryllium chips, may result. A large side cutting angle is used to ensure that the impact load will be taken at a point back of the nose. It will also ease the tool out of the cut at the end of the piece. Excessive angles, however, will lead to chatter. The end cutting edge angle should be large enough to permit the tool to clear the work and prevent rubbing. The nose radius, 0.015625 to 0.03125 inch, should be omitted when heavy cuts are to be made.

Table XIII. Tool Design for Lathe Operations[46]

Tool Geometry	Turning	Forming
Back Rake Angle (degrees)	0	8
Side Rake Angle (degrees)	7 to 8	None
Side Cutting Edge Angle (degrees)	12 to 15	None
End Cutting Edge Angle (degrees)	8 to 15	None
Side Relief Angle (degrees)	7 to 10	7
End Relief Angle (degrees)	7 to 10	7
Nose Radius, Continuous Cutting (inch)	0.015625 to 0.03125	None
Nose Radius, Interrupted Cutting (inch)	0.0625	None

Recommended speeds, feeds, and depths of cut for beryllium are given in Table XIV. Although speeds and feeds comparable to those used for machining cast iron may be used for machining beryllium, lower speeds normally are necessary to permit clean chip salvage and dust removal.[46] Feeds should not be over 0.015 inch per revolution to prevent rough finishes and breakouts on edges. Extremely fine feeds also must be avoided since they tend to dull tools faster and heat the beryllium more than the heavier cuts. Critical inspection of parts for possible surface cracks is required. Cuts deeper than 0.0625 inch may create a safety hazard if the exhaust system is unable to remove chips efficiently.

Tracer equipment on engine lathes is widely used in machining beryllium.[46] The equipment consists of a hydraulic or electronic tracer positioned so that the cutting tool follows the track of a stylus along the contours of a master model or pattern. Tracer equipment is important in turning beryllium because, until recently, complex shapes and geometries could not be obtained in beryllium by methods used for other metals. With tracer equipment, a fabricator can achieve quantity production of beryllium hardware on conventional lathes without loss of reproducibility. Thus, precise dimensional tolerances can be maintained over long runs, approaching semiautomatic operations without large investments in capital equipment.

5. Milling

The milling of beryllium closely follows the practice used in turning operations. Conditions and techniques regarding grades of cutting tools, chipping of work, speeds, feeds, and safety are similar. Conventional milling, rather than climb milling, is recommended to obtain the best finish and most economical use of cutters. Since beryllium tends to chip as the cutter leaves the work, suitable backup materials such as free-cutting steel should be used. The steel chips can be removed readily from the beryllium chips by a magnetic separation.

Table XV gives recommendations for tool design for milling beryllium. Carbide cutters are recommended for milling beryllium for the same reasons they are used for turning operations. Inserted carbide tooth cutters of grade C-1 carbide are used for rough milling while carbide grade C-2 cutters are used for finish milling.

Recommended feed, speed, and depth of cut for milling beryllium are given in Table XVI. Milling speeds must be selected on the basis of efficient chip disposal and minimum airborne dust as well as the size of the piece, the rigidity of the setup, and the depth of cut.

Water soluble oils or emulsions may be used as coolants diluted one part of oil to 20 to 30 parts of water. If large quantities of beryllium chips are to be removed, it is often more profitable to machine dry, provided an adequate ventilation, exhaust, and chip disposal system is available, than to separate the chips from the coolant and clean them after machining.

Table XIV. Speed, Feed, and Depth of Cut for Lathe Operations[46]

Speed, (fpm)	150 to 250*
Feed (ipm)	0.005 to 0.015
Depth of Cut (in.)	To 0.100
Horsepower	1 hp per cu in. per minute

* Speeds up to 1000 fpm may be used for very short intervals.

Table XV. Tool Design for Milling Beryllium[49]

Tool Geometry	Rough and Finish Milling
Back-rake angle (degrees)	0 to 10
Side-cutting edge angle (degrees)	7
Face-cutting-edge angle (degrees)	3 to 7
Side-relief angle (degrees)	10 to 15
End-relief angle (degrees)	10 to 15
Land (in.)	1/32 to 1/16

Table XVI. Speed, Feed, and Depth of Cut for Milling Beryllium[49]

	Roughing	Finishing
Speed (fpm)	60 - 100	100 - 150
Table Feed (ipm)	3 - 6	3 - 6
Depth of Cut (in.)	No data	No data

6. Trepanning

Using current fabrication practice, over 90 percent of finished beryllium parts used today are machined from vacuum hot-pressed billets. These are limited for the most part to solid cylinders, blocks, or slabs. The value of the metal dictates that solids rather than chips should be salvaged whenever possible because other products often can be machined from such stock. Because of this consideration, holes over 2 inches in diameter usually are trepanned. This need has resulted in the development of some interesting tooling for conical and spherical shapes in addition to plain cylindrical work. In general, trepanning tool design must be a compromise between the rigidity of the tool and the narrowness of the kerf.

For other than straight cylindrical cutting, this compromise often means a multiplicity of parting blades. In addition, complicated follower rests have been designed to strengthen the tool and minimize chatter. In spite of the necessity for producing the highly specialized tools, the cost of tooling, together with the actual cost of trepanning, is usually quite negligible when the value of the bervllium metal that can be salvaged is considered.

Figure 17 shows a technique of trepanning four separate cones from a cylinder of beryllium by means of a special angle tool. The tool cuts away all of the beryllium in the cylinder except that indicated by the shaded areas. This results in four individual truncated cones machined from a cylinder of beryllium. This is merely one example of present day techniques that are used to fabricate beryllium into shapes.

7. Sawing

Cutting of cylindrical, rectangular, or hexagonal vacuum hot-pressed beryllium block into workable sizes and shapes is usually a cutting or sawing operation. The slicing of large blocks permits savings compared to the cost of producing an equal weight of small individual pressings.

A bandsaw is used to slice hot-pressed billets as large as 36 inches. Because of the value of the metal, the kerf must be held to an absolute minimum, and bowing or wandering of the bandsaw must be rigidly controlled. Bowing usually is the result of inadequate tension or preferential wear on the bandsaw teeth. The Beryllium Corporation has equipped its large bandsaw with strain gages to detect bowing of the saw and to measure cutting forces.

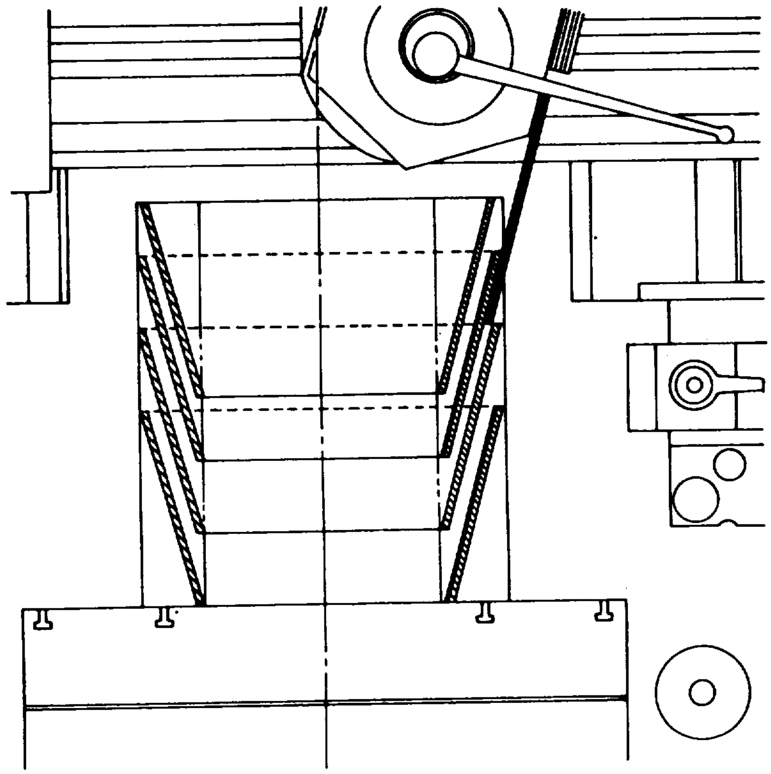

Figure 17. Trepanning of Four Individual Truncated Cones from a Beryllium Cylinder[46]

The strain gage measuring cutting force indicates when the feed rate should be adjusted to ensure optimum cutting efficiency. A limit switch on the other strain gage automatically stops the saw before the cut can wander enough to damage the work. Thus, the strain gages serve two distinct functions: 1) they warn of incipient bowing and 2) they indicate cutting forces required, the latter being a reliable indication of cutting efficiency.

The relationship between saw speeds and feeds for various thicknesses of beryllium when cut with 1- and 2-inch wide bandsaws is shown in Table XVII. The 1-inch wide bandsaw has a clawtooth blade, 6- to 10-pitch, 0.040-gage, and 0.060-inch set for work up to 3.0 inches thick. For thicker stock, a clawtooth saw 2.0 inches wide, 2-pitch, 0.050-gage, and 0.070-inch set is recommended.

Table XVII. Recommended Saw Speed and Feed for Various Thicknesses of Beryllium[45]

	Work Height (in.)	Saw Speed (sfpm)	Feed (sq in./min)
1-In. Saw	1/8 - 1	150 - 100	15 - 10
	1 - 3*	100 - 85	10 - 5
2-In. Saw	3 - 6*	150	10 - 7
	6 - 10	150	7 - 4
	10 - 20	145 - 125	2 - 1
	20 - 30	125 - 112	1-1/2 - 1
	30	100 - 95	1

* The apparent inconsistency of the bandsaw speeds for the 1- to 3-inch and 3- to 6-inch range of work is explained by the additional beam strength afforded by the 2 inch wide blade and also because this blade can be accompanied only on a machine of the bandmiller type, which provides for greater rigidity in addition to positive table feed.

8. Grinding

Ordinarily it is not necessary to grind beryllium because the finishing cuts by machining will give the required finish if tools are in good condition. Beryllium can be ground to produce shapes with close tolerances and sharp edges. Usually only a few thousandths of an inch of metal are removed by grinding. Rough grinding is done on coarse grained aluminum oxide wheels with a soft grade vitrified bond. Fine finish grinding is done with wheels having medium grain, medium hardness abrasives. All grinders must be properly hooded for removal of airborne dust by means of the pneumatic system.

If further information on the machining of beryllium is desired, see TM X-53453, The Fabrication of Beryllium - Volume III: Metal Removal Techniques for Beryllium Alloys.

SECTION VII. POSTFABRICATION TREATMENTS

In the procedures for commercially fabricating beryllium into parts or shapes, it is necessary to give the structure a postfabrication treatment to improve the strength and also the ductility properties of the part. Such treatments may consist of chemically etching, stress relieving, or recrystallization heat treatments.

1. Chemical Etching

Mechanical deformation of wrought beryllium products results in the buildup of significant stresses.[46] Shearing processes, such as machining operations, result in undesirable surfaces stress conditions or even fine surface damage. Development programs at prime space vehicle centers have verified that these conditions exist.

Using proper machining procedures, surface damage is limited to only 0.001 to 0.002 inch but this is sufficient to significantly affect the performance of stressed parts. For these reasons, it is recommended that cutting and grinding operations be followed by acid etching to completely remove the damaged surface layers. Since these layers rarely extend below the immediate surface, the removal of 0.002 to 0.004 inch from each surface is adequate to eliminate all such potential problem areas.

Table XVIII lists solutions commonly used to etch beryllium. These solutions are recommended for specific operations and are not interchangeable. In use, etching rates should be established and checked periodically with test coupons to maintain the effectiveness of the etching bath. All etching should be performed with good circulation of the etchant. If any excessive localized pitting occurs during etching, the composition of the bath should be adjusted or the bath should be replaced. The etching process liberates heat which greatly affects the rate of reaction. Therefore, when etching relatively large parts or large numbers of parts, suitable means must be employed to control the temperature of the etching bath.

In the commercial production of the beryllium shell for the spacer used as a component in the Minuteman missile, over 200 holes are drilled. The procedure followed is to drill the holes slightly undersize and then etch the entire spacer to remove 0.002 inch from all surfaces. This etching procedure brings the drilled holes to size for efficient assembly of the spacer.

Mebs and Smith[51] found that room temperature tensile properties of beryllium are significantly affected by surface preparation. Using

Table XVIII. Solutions Used to Etch Beryllium[46]

Operation	Composition of Etchant	Temperature (°F)	Estimated Rate of Removal From Each Surface
Rough etching chemical cutting	10 - 20% H_2SO_4	70 - 90	0.005 in./min
Matt finish deoxidation and finishing machined surfaces	25% HNO_3 + 0.25% HF*	70 - 90	0.001 in./5 min
Reflective finish after deoxidizing etch	53 g chromic anhydride 26.5 mm conc. H_2SO_4 450.0 mm ortho-phosphoric acid	70 - 90	0.001 in./5 min

* The concentrations of nitric and hydrofluoric acids can be increased to 40 and 2 percent, respectively, to obtain increased rates of etching.

vacuum hot-pressed beryllium and press-forged beryllium, containing approximately 2.1 percent beryllium oxide, they found that wet machining produces more surface damage than dry machining. Chemically etching to remove 0.0025 inch from all surfaces significantly increased the elongation in a tensile test. However, no further improvement was obtained when 0.005 inch was removed from the surface.

Ward, Jacobsen, and Mathews[52] also report that defects introduced in beryllium sheet by machining can be removed only by chemical etching. They etched off 0.002 inch from all surfaces to obtain sheet relatively free of defects.

2. Heat Treatments

Two types of heat treatment, strain relieving and annealing, are commonly used with beryllium that was deformed either by forging, rolling, extrusion, or forming. Some of these heat treatments have been discussed in previous sections and, therefore, will not be described in great detail in this section.

a. Stress Relief

Stress relieving involves heating to a suitable temperature, holding long enough to reduce residual stresses, and then cooling slowly enough to minimize the development of new residual stresses. For beryllium that has been fabricated in one manner or another, the deformation is accompanied by the accumulation of residual stresses of significant magnitude.[32] These stresses have important effects on the strength of the structure under service loads and on the propagation of cracking, once failure is initiated. Producers, therefore, recommended that all wrought shapes of beryllium be stress relieved following deformation. Stress relieving temperatures in the range of 1300° to 1400°F are most effective in accomplishing adequate stress relief although stresses may be relieved with long exposures at temperatures as low as 1150°F. Temperatures above 1400°F are likely to cause recrystallization and grain growth, thus, destroying the favorable properties of the wrought product. Usually stress relieving times of 10 to 20 minutes are adequate.

Sometimes forgings are stress relieved at slightly higher temperatures and for longer times than those mentioned above. Hayes and Yoblin[30] for example, reported stress relieving forgings at 1400° to 1470°F for times ranging from 0.5 to 1.0 hour.

Guest, et al.,[21] report stress relieving extruded products as quickly as possible after extrusion at 850°C (1562°F) and then slow cooling to approximately 200°C (392°F) over a period of 40 hours to improve ductility.

Ward, Jacobsen, and Mathews[52] report marked improvements in the ductility of beryllium sheet by heating at 400°F. This temperature is considerably lower than is normally employed for stress relieving.

b. Annealing

At times it is desirable to anneal beryllium that has been heavily worked to prepare the metal for additional fabrication. The term "annealing" for beryllium, as for other nonferrous metals, implies a heat treatment designed to soften a cold-worked structure by recrystallization or subsequent grain growth or to soften an age-hardened alloy by causing a complete precipitation of the second phase (overaging) in relatively coarse form.

Bort and Moore[53] report that, with optimum working and annealing conditions, uniform and equiaxed grain sizes of approximately 30 microns have been achieved in rolled ingot sheet. The sheet was produced by rolling vacuum cast electrolytic flake metal. Recrystallization times at 1000°C (1832°F) ranged from 15 seconds to 4 minutes. Very small specimens were heavily deformed by rolling at 200° to 500°C (392° to 932°F) to the maximum amount of work prior to fracture. Using a multistage process (warm roll, anneal, stress relieve, warm roll, anneal, etc.), the grain size can be refined from 100 to 30 microns which increases the tensile elongation at 20°C (68°F) from 1 to 12 percent.

Spangler, et al.,[54] reported that a zone purified, Pechiney beryllium bar could be recrystallized by heating at 705°C (1382°F) for 15 minutes following 70 to 80 percent reduction by swaging at 425°C (797°F). However, annealing at 500°C (932°F) for 30 minutes did not cause recrystallization. These same investigators[55] stated in a later report that commercial vacuum hot-pressed and extruded rod, swaged to wire, recrystallized when heated at 800°C (1472°F) for 1 hour. Swaged, S R Pechiney beryllium recrystallized at 600°C (1112°F). Swaged, zone refined very pure wire formed equiaxed grains as low as 350°C (662°F). This latter material was extremely ductile; a 0.024 inch diameter wire was bent 240 degrees around a 0.1875 inch diameter pin before breaking. The rate of grain growth of the zone refined material is much more rapid above 600°C (1112°F) than the

S R Pechiney grade while the grain growth of the commercially pure beryllium is extremely slow even at 900°C (1652°F). Presumably the slower grain growth in the less pure beryllium is the result of the oxide and other impurity products in the grain boundaries of these powder metallurgy products. Rapid grain growth in the zone refined beryllium takes place because of the relative absence of these interfering impurities between the grains.

Barrow and Craik[27] reported that annealing at 700° to 875°C (1292° to 1607°F) for 24 hours caused complete recrystallization in Pechiney ingot sheet but did not recrystallize sheet made from commercial hot-pressed powder. Further grain refinement was obtained in the ingot sheet by open-press forging the preforged ingot sheet at 600°C (1112°F) followed by annealing at 705°C (1382°F) for 12 hours.

Gross and O'Rourke[36] found that fine-diameter high-purity wire from zone-refined beryllium could be recrystallized by annealing at 1500°F for 30 minutes after warm swaging. Such wire which was less than 0.010 inch in diameter could then be deformed into finer wire by warm working.

3. Discussion

In some instances, it is not convenient or practical to give beryllium sheet structural parts a final stress relief or etch after all drilling has been completed. It is, therefore, desirable to know if one or both of these steps can be eliminated without causing a significant decrease in the tensile strength or fatigue life of such parts. In addition, it is also desirable to know if processes other than conventional hole drilling can be used that would not require a final stress relief or etch.

To determine some of these answers, Brush Beryllium Company conducted tests to evaluate the effects of different hole-preparation procedures on the strength of beryllium sheet material.[56,57,58] In the first series of tests, 12 standard sheet tensile specimens were machined, stress relieved, and etched from a single cross-rolled sheet of commercial vacuum hot-pressed block. A 0.125 inch diameter hole was then drilled at the midpoint of the 2-inch gage length as shown in Figure 18, using a conventional drill in six of the specimens. Five of the remaining six specimens were drilled using electrical discharge drilling methods and the sixth specimen was left undrilled for use as a control.

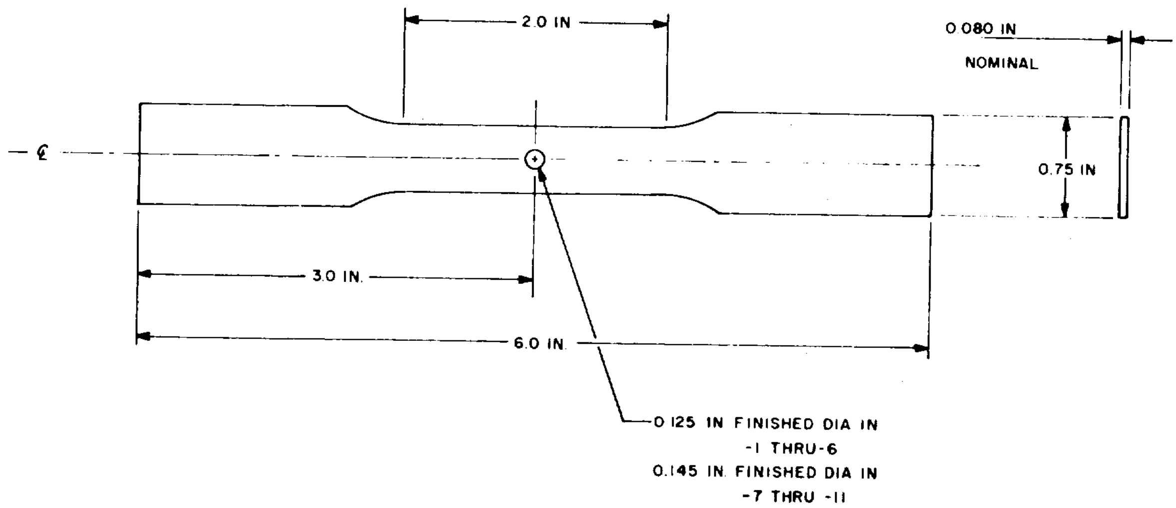

Figure 18. Standard Sheet Test Specimen Used in First Series of Tests[56]

Data in Table XIX for specimens treated in various ways after drilling show that for holes drilled conventionally, it is necessary to either stress relieve or etch the sheet but not both, after drilling. Holes in beryllium sheet produced by electrical discharge machining with certain settings (Elektro Jet Machine) did not need to be either stress relieved or etched. Lapping after conventional drilling is not effective in increasing strength. The ratio f_{net}/f_{tu}, shown in the last column of Table XIX, is the ratio between the ultimate strengths of the variously treated drilled specimens and that of the undrilled specimen. High ratios are desirable.

Similar tests were performed using the specimens and test fixtures shown in Figures 19 and 20. The data obtained from these three experiments are summarized in Figure 21. The following conclusions can be drawn from this series of experiments:[58]

If conventional hole-drilling techniques are used, a final stress relief or etch, but not both, is necessary to develop high net tensile stresses.

If holes are produced by electrical-discharge drilling under certain conditions, neither stress relief nor etching is required to produce high net tensile stresses.

Table XIX. Effect of Postdrilling Treatment on the Tensile Stress and Elongation at Failure of Standard Sheet Tensile Specimens Made from Commercially Pure Beryllium Sheet[56]

Specimen	Method of Drilling	Stress Relief	Etch	Lap Hole	Net Stress at Failure (10^3 psi)	Elongation Over 2 Inches (%)	$\frac{f_{net}}{F_{tu}}$
-12 (Controls)	No hole	Yes	Yes	--	68.1	14.0	1.0
	No hole	Yes	Yes		67.5	13.9	1.0
- 1	Conventional	No	No	No	32.4	0	0.48
	Conventional	No	No	No	36.1	0	0.53
- 2	Conventional	Yes	No	No	60.7	1.7	0.90
	Conventional	Yes	No	No	57.9	1.5	0.85
- 3	Conventional	No	Yes	No	56.5	1.2	0.83
	Conventional	No	Yes	No	58.7	1.4	0.87
- 4	Conventional	Yes	Yes	No	61.0	2.0	0.90
	Conventional	Yes	Yes	No	61.5	2.0	0.91
- 5	Conventional	No	No	Yes	37.0	0	0.55
	Conventional	No	No	Yes	34.4	0	0.51
- 6	Conventional	Yes	No	Yes	39.0	0	0.58
	Conventional	Yes	No	Yes	37.5	0	0.55
- 7	Elektro Jet Tap 1	No	No	No	60.9	1.2	0.90
	Elektro Jet Tap 1	No	No	No	58.2	1.3	0.86
- 8	Elektro Jet Tap 2	No	No	No	46.4	0.5	0.68
	Elektro Jet Tap 2	No	No	No	59.9	1.0	0.88
- 9	Elektro Jet Tap 3	No	No	No	61.6	1.3	0.91
	Elektro Jet Tap 3	No	No	No	55.9	1.3	0.82
-10	Elektro Jet Tap 3	Yes	No	No	60.8	1.3	0.82
	Electro Jet Tap 3	Yes	No	No	59.5	1.5	0.88
-11	Elektro Jet Tap 3	No	Yes	No	63.4	1.5	0.93
	Elektro Jet Tap 3	No	Yes	No	59.5	1.5	0.88

Notes: Stress-relieving operation - 1385°F for 20 minutes;
etching operation - 0.002 inch per surface in nitric-HF;
lapping operation - 0.001 inch on diameter.

-1 through-11 specimens were stress relieved and etched after contouring to size and prior to hole drilling.

On Elektro Jet Tap 1, Tap 2, and Tap 3 is maximum, three-quarter, and one-half power, respectively.

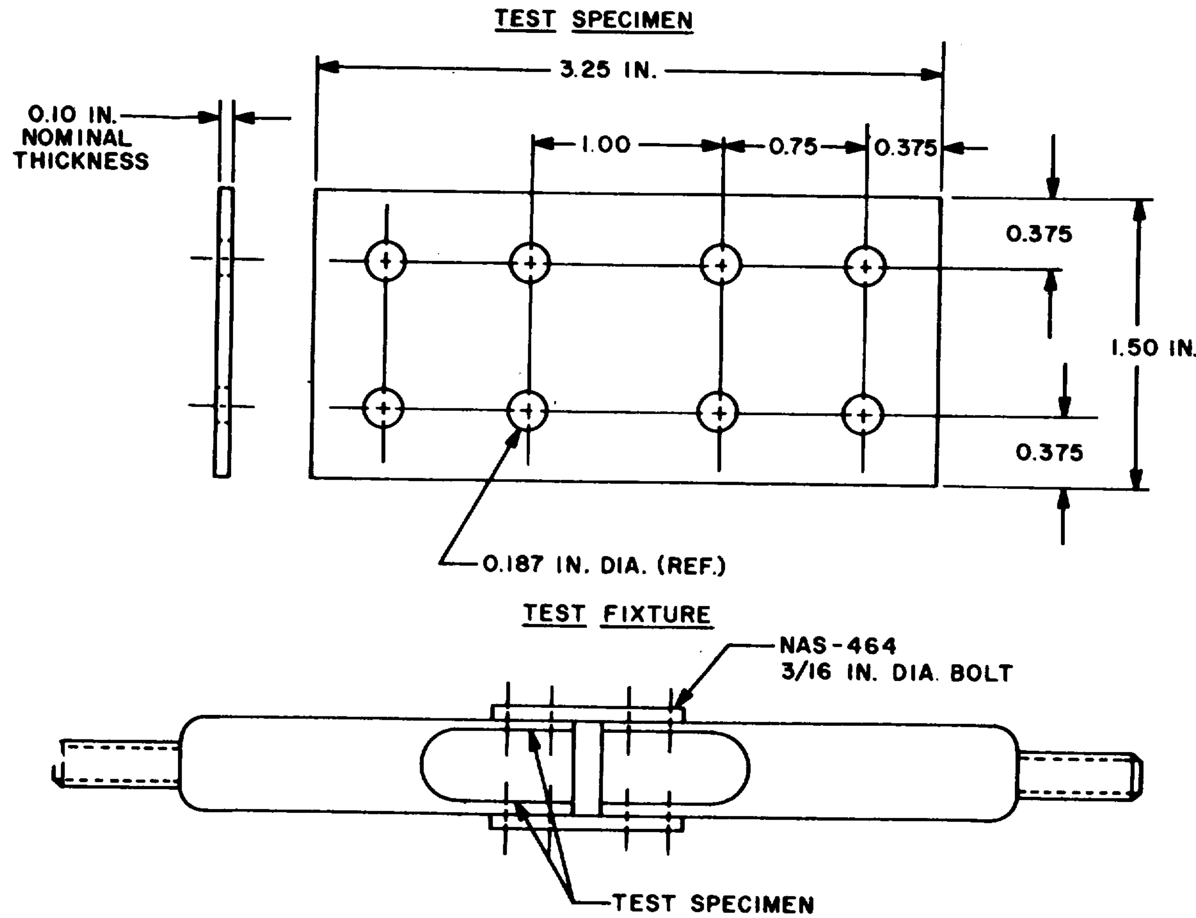

Figure 19. Test Specimen and Fixture Used for Second Series of Tests[57]

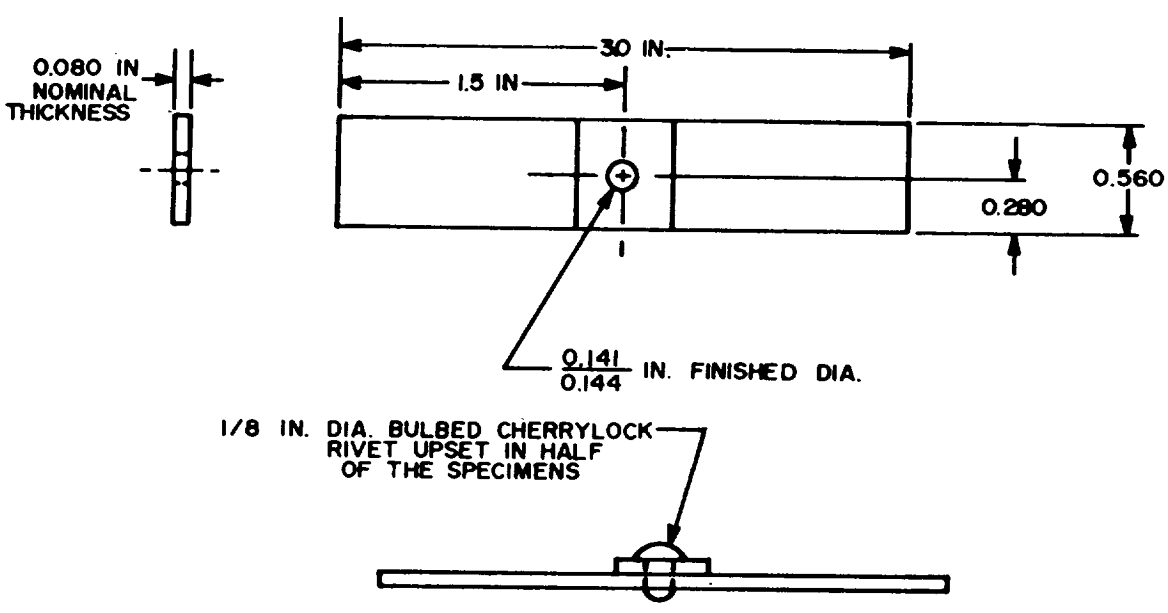

Figure 20. Test Specimen Used in Third Series of Tests[58]

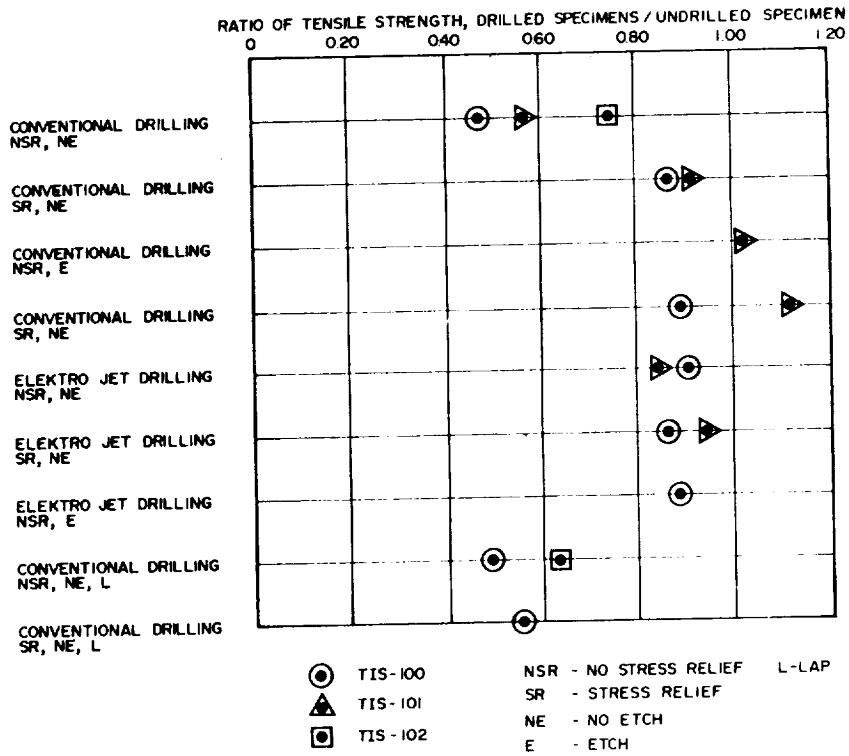

Figure 21. Summary of Data Showing the Effects of a Number of Postdrilling Treatments on Net Tensile Stresses in Drilled Beryllium Sheet[58]

Lapping of conventionally drilled holes is not effective; net tensile stresses were no higher than in unlapped holes.

Specimens with unfilled holes developed net tensile stresses as high as those with rivets.

If further information on post fabrication treatments of beryllium is desired, see TM X-53453, The Fabrication of Beryllium - Volume IV: Surface Treatments for Beryllium Alloys, and Volume V: Thermal Treatments for Beryllium Alloys.

SECTION VIII. JOINING METHODS

For many applications, prefabricated beryllium parts must be assembled by one of several joining methods.[19] These pieces of hardware may include air frame and missile sections, nuclear fuel elements, and associated hardware, and assembled instruments, especially those of the inertial guidance type.

All methods of joining normally used in commercial manufacture appear quite applicable to beryllium. These include mechanical fastening with rivets and bolts (the fasteners may be made of beryllium or other metals); adhesive joining as with epoxy resins and other organic compounds; soldering; furnace brazing; braze welding; various inert gas, electric arc welding procedures; resistance, projection spot, butt, flash, and seam welding; autogenous pressure welding; ultrasonic welding; and electron beam welding.

Table XX[59] gives a comparison of joints obtained with beryllium by several joining methods. It can be seen that properly prepared brazed joints have highest joint strengths with welded joints almost as strong, but less ductile. The zinc solder produces a rather high strength joint compared to the other solders listed. Epoxy joints lose strength rapidly with temperature.

1. Mechanical Fasteners

It is reported[60,61] that on a strength to weight basis, beryllium bolts are stronger in all respects, but more costly, than bolts made of steel or titanium of suitable configuration for similar applications. The room temperature, double shear strength of bolt shanks was over 60,000 psi (65 percent of the strength of the base material tensile strength for beryllium versus 60 percent for steel and titanium). This is equivalent to 400,000 psi steel and 200,000 psi titanium on a strength to weight basis. Beryllium is not recommended, however, for tension-type fasteners because of its high degree of notch sensitivity.

Best bolt properties were obtained by upset forging commercially pure hot-pressed beryllium extruded bar stock at 1450° to 1500°F. Threads subsequently were rolled to the MIL-S-7742 thread profile modified for a rounded root specification. Best thread depth to the point of tangency of the root was 55 percent of the theoretical depth. Aluminum nuts were found to be superior to steel nuts for use with beryllium bolts and could be reused many times. Bolts with rolled threads had tensile strengths 50 percent higher than those with

Table XX. Comparison of Joints Obtained Through Several Processes[59]

Process	Type of Joint	Joining Material	Temperature of Test	Fracture Stress	Comments
Adhesive Bonding	Overlap	Epoxy Resin	RT 300°F	3,000 + psi shear 300 psi shear	Adhesive coated on both surfaces before joining
Soldering	Overlap	5% indium Ag-Pb solder	RT	3,000 psi shear	Pieces pretinned before joining
		3% Zn-Sn-Pb	RT	3,000 psi shear	Pieces pretinned before joining
		99.9% Zn	RT	9,000 + psi shear	Pieces pretinned before joining
Brazing	Overlap	Al-12% Si	RT 500°F	20-30,000 psi shear	Furnace brazed assemblies
	Butt type	Al-12% Si	RT	20,000 psi tensile	No reinforcement
	Butt type	Al-12% Si	RT	30,000 + psi tensile	30% reinforcement
	Overlap	Ag-0.5% Li	RT	20,30,000 psi shear	Furnace-brazed assemblies
	Butt type	Ag-0.5% Li	RT	30,000 + psi tensile	Braze-welded assemblies--as brazed--30% reinforcement
			1200°F	10,000 psi	Braze-welded assemblies--30% reinforcement
	Butt type	Ag-0.5% Li	RT	35-45,000 psi	Braze-welded assemblies--stabilized 5 hours at 1200°F--30% reinforcement
Welding	Butt type	Beryllium	RT	25-30,000 psi tensile	Low ductility exhibited by weld and heat-affected zone
			800°F	15-20,000 psi tensile	

machined threads. Best shear properties were obtained by etching in a chromic phosphoric sulfuric acid bath.

Bolts were thoroughly inspected by fluorescent penetration techniques after chemical etching to ensure the use of sound materials. Except for the necessary exhaust systems required when machining and grinding to protect operators from the toxic beryllium dust, it was found that beryllium bolts can be produced using standard fastener producing methods.

Threaded aluminum stud fasteners can be used to join beryllium sheet to other metals.[61] Standard stud welding equipment is used to attach the aluminum base alloys, usually 4043 or 6061, to the beryllium sheet. The studs can develop tensile strengths approaching those of stud welded aluminum assemblies. Beryllium studs are not recommended because of their low ductility, and ferrous and copper-base studs have been tried without success.

Threaded metal screws with chamfered heads also can be used to attach beryllium paneling. The screws can be bonded, soldered, or brazed into holes with matching chamfers in the sheet. Beryllium screws (0.125 to 0.25 inch NF threads) may be used for this type of fastener to achieve maximum savings in weight, since on a weight basis they are several times lighter than competing aircraft bolting materials.

Satisfactory joints in beryllium also have been made by using heat resistant stainless steel fasteners.[33] Hole requirements are similar to those used for aircraft practice. Greater edge distances than normal (minimum values of 2.5 times the hole diameter) are recommended because of the brittleness of beryllium. On the basis of tests at room temperature, at 800°F, and at 1400°F with some typical joint configurations, it was found that a double row of mechanical fasteners is approximately 40 percent stronger than a single row. Failures usually occurred in the beryllium sheet as a result of stress concentration at the fastener hole. Most structural joints in current beryllium hardware design use countersunk mechanical fasteners and in general a single row of fasteners has been adequate to carry the design loads.

2. Adhesive Bonding

Adhesive bonding produces joints in beryllium that may be as strong as some soldered joints at room temperature but lose their strength rapidly even at slightly elevated temperatures. Table XX shows that at 300°F, the strength of an epoxy joint was only about 10 percent of that found at room temperature.[59]

Work at Lockheed[33] indicates that beryllium can be successfully adhesive bonded with Specification MIL-A-8431 Type II Adhesive (Bloomingtondale Rubber HT-424). Specimens tested at room temperature, at 1000°F, and at 1200°F showed the following shear strengths:

Temperature (°F)	Bond Shear Strength (psi)
68	3600
1000	880
1200	470

This adhesive has somewhat better elevated temperature strength than the epoxy listed in Table XX.

Resin bonding can be accomplished in beryllium using epoxy phenolic resins and standard procedures commonly used to bond aluminum.[59] Care must be used in preparing the specimen to ensure a satisfactory bond. Cleaning for bonding can be accomplished by etching for 10 minutes at 140°F in a 10 percent sodium hydroxide solution followed by rinsing and air drying. The deoxidizing etch may also be used. After coating with resin and assembling in fixtures the resin is cured under pressures of 10 to 15 psi at 275°F. Bonds produced in this manner have room temperature shear strengths of 3000 psi.

3. Soldering

Brazing and mechanical fastening are reliable and have proven to be valuable fastening procedures. Some applications exist, however, where a metallic attachment or seal must be made to beryllium, but the conditions are such that brazing must be avoided. Here soldering finds usage.

Early work indicated that beryllium could not be soldered by procedures, fluxes, and solders used for copper. A recent comprehensive study at The Beryllium Corporation[62] has now established the fluxes and procedures required for soldering beryllium metal. This study determined the wettability of over 20 elements and combinations of elements. Elements comprising these soldering alloys included tin, lead, zinc, indium, silver, bismuth, cadmium, aluminum, and copper.

The alloys, with one exception, were either zinc, lead, or indium base alloys. The one exception was a bismuth-base alloy.

These authors[62] concluded that good flow and wetting seem to coincide with high joint strength. This can be seen in Table XXI. On the basis of strength, wetting, and flow properties, the high zinc solders are best. The only negative factor is their comparatively high melting temperatures which puts them at the borderline between brazing and soldering. The strength of joints soldered with high zinc alloys is within an order of magnitude of the properties of brazed joints and several times greater than the strength of adhesive bonded joints.

In applications where the required joint strengths are not as high and the ease of accomplishing a seal or contact is more important, the use of lead base solders containing additions of indium, zinc, or silver are to be preferred because of their lower soldering temperatures. Precoating of the beryllium is recommended as a soldering procedure. Since reaction type fluxes are required to wet the beryllium by the solder, the fluxes must be removed and neutralized after joining to prevent corrosion. Surface preparation, therefore, should include degreasing, acid etching, and thorough rinsing.

In a previous study, Keil, Hanks, and Taub[63] had found soft soldering to be an effective joining method when the design could incorporate a press fit in the joint. The most effective solders and surface treatments found in this study were the following:

Solder composed of Pb-31 wt % Sn-26.8 wt % Zn on silver, flame-sprayed beryllium

Solder composed of Pb-50 wt % Sn on beryllium coated with Sn-50 wt % in using a tin chloride flux

Solder composed of Sn-8 wt % Zn-1 wt % Ni on copper-plated beryllium

Solder composed of Sn-20 wt % Ag-3 wt % Cu-2 wt % Zn on copper-plated beryllium.

These authors investigated nine different solder compositions and a number of precoating and fluxing methods. The soldering was carried out in air under ventilation.

Details on the soldering of beryllium are described[59] which indicate that soldered joints can best be made with either pretinned surfaces

Table XXI. Characteristics of Soldering Alloys used on Beryllium[62]

Series	Sn	Pb	In	Zn	Other	Solidus Temp. (°F)	Liquidus Temp. (°F)	Soldering Temp. (°F)	Average Contact Angle (deg)	Order of wettability	Flow Area (sq in.)	Order of Flowability	Average Shear Strength (psi)	Order of Strength
1	-	100	-	-	-	621	621	680	4	1	0.2844	9	1,236	17
2	25	75	-	-	-	361	514	560	7	5	0.2633	11	1,822	9
3	40	60	-	-	-	361	460	500	11.5	8	0.1144	19	2,265	7
4	50	50	-	-	-	361	423	480	31.5	22	0.1544	15	1,360	14
5	60	40	-	-	-	361	370	450	-	-	0.1455	17	1,794	10
6	100	-	-	-	-	450	450	500	24.5	17	0.0355	29	-	22
7	-	95	5	-	-	559	598	565	4	18	0.2425	12	2,033	8
8	-	75	25	-	-	440	508	475/550	13/14	9/10	0.0725	24	1,630	11
	-	-	-	-	-	-	-	580	15	12	0.1000	22	-	-
	-	-	-	-	-	-	-	-	-	-	0.2678	10	-	-
9	-	50	50	-	-	356	408	470	21	14A	0.1100	20	1,612	12
10	-	-	100	-	-	313	313	365	27	20	0.1525	16	444	20
11	-	-	90	-	10 Ag	286	460	475	26	19	0.1075	21	1,092	18
	-	-	-	-	-	-	-	560	25	18	0.500	3	-	-
12	50	-	50	-	-	243	257	320	63	24	0.036	28	1,340	15
13	-	-	-	100	-	787	787	840	6	4	1.500	1	11,000*	1*
14	34	63	-	3	-	338	492	550	14.5	11	0.1205	18	2,661	5
	-	-	-	-	-	-	-	650	5	3	1.120	2	-	-
	-	-	-	-	-	-	-	500	17.7	13	-	-	-	-
15	-	93	5	-	2 Ag	536	545	580	21	14B	0.2911	8	2,595	6
16	-	90	5	-	5 Ag	554	554	550	11	7	0.0950	22	2,812	4
	-	-	-	-	-	-	-	650	-	-	0.4089	4	-	-
17	-	15	80	-	5 Ag	300	300	360	30	21	0.1725	14	1,362	13
18	70	18	12	-	-	302	345	420	48	23	0.0420	26	1,239	16
19	38	37	25	-	-	280	280	355	64	25	0.0530	25	1,045	19
20	11	22	18	-	41 Bi	212	230	280	-	-	0.0375	27	305	21
	-	-	-	-	8 Cd	-	-	340	-	-	0.3478	6	-	-
21	-	-	-	95	3 Al	705	720	770	21	14C	0.3720	5	10,000*	2*
	-	-	-	-	2 Cu	-	-	-	-	-	-	-	-	-
22	41	-	-	59	-	390	690	730	10	6	0.3350	7	6,000	3

* Base-metal fractures.

or surfaces zincate treated and then plated with silver or copper. Standard solders, fluxes, and procedures can be used to solder directly to the zincate treated surfaces. With this latter method, care must be exercised to ensure complete plating of the surfaces.

4. Brazing

Brazing and soldering are both methods of joining metals by flowing a thin layer capillary thickness of filler metal in the space between the two metals. Bonding results from the intimate contact produced by the dissolution of a small amount of base metal in the molten filler metal without fusion of the base metal. The term brazing is used when the temperature exceeds some arbitrary values such as 800°F; soldering is used for temperatures below the arbitrary value.

When the filler metal is put in place as a thin solid sheet or as a clad layer and the composite heated, the process is called furnace brazing. Braze welding is welding in which a groove, fillet, plug, or slot weld is made using a filler metal having a melting point lower than that of the base metal but higher than 800°F. The filler metal is not distributed by capillarity in this case.

Considerable research has been devoted to developing a satisfactory brazing technique for joining beryllium to itself and to other metals.[33] The silver base alloys are probably the most satisfactory, with brazing temperatures slightly above the beryllium silver eutectic temperature, 1620°F. Pure silver, pure silver plus lithium, silver copper alloys with or without lithium, and aluminum silicon alloys have been found to develop reasonably good shear strengths as brazed joints.[59, 33] Figure 22 illustrates some typical joints that can be produced by brazing beryllium.

The brazing time as well as the time to heat and cool beryllium specimens above the beryllium silver eutectic temperature must be as short as possible to minimize the formation of beryllides.[33] A practical brazing cycle using pure silver would consist of brazing at 1660°F for 2 to 5 minutes in a vacuum of at least 10^{-4} mm of mercury; fluxes or good inert gas atmospheres may be used instead of vacuum. In addition to minimizing formation of beryllides, the short brazing time also minimizes grain growth in the beryllium parent metal sheet which probably had been finish rolled at a temperature lower than the brazing temperature.[59]

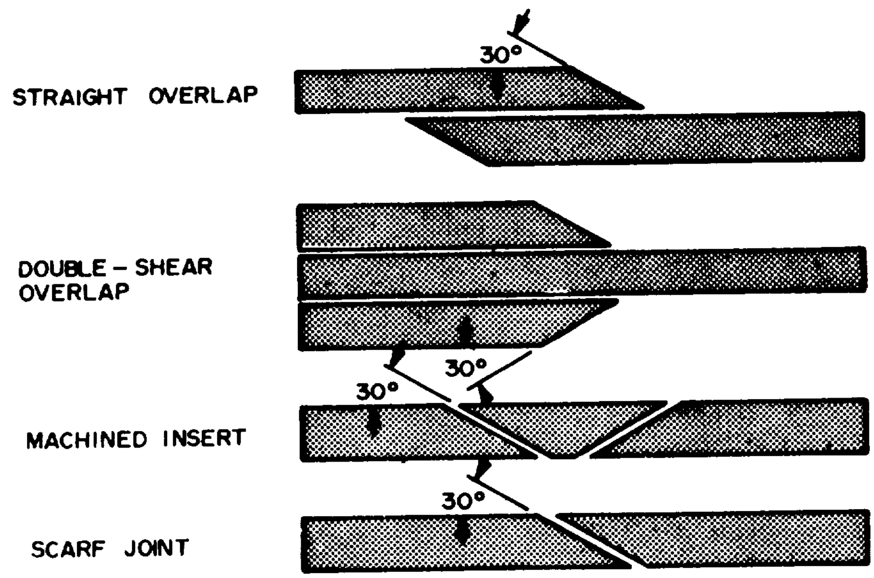

Figure 22. Typical Joint Design for Furnace Brazing[59]

Drusos, et al.,[64] describe three techniques for fast heating and cooling of sandwich panels to prevent grain growth during brazing. These include the quartz lamp, the electric blanket, and the furnace methods. In the quartz lamp method, the brazing envelope and panel are heated by banks of quartz lamps. After holding for the required time, the assembly suspended from an overhead track is cooled by clamping between two heavy steel platens. In addition to removing heat, the platens also keep the panel flat. Rapid, even temperature and close control of temperature are advantages of this method.

Results produced by electric blanket brazing are similar to those obtained by quartz lamp heating. The retort was sandwiched between heated dies until the brazing temperature was reached. Cooling was accomplished by immediately introducing compressed air into plenum chambers that feed air through holes in the die faces, cooling the die and the retort at the same time.

Curved shapes, not suitable for either the quartz lamp or electric blanket brazing techniques, were placed on a hollow mandrel to allow for rapid heating and cooling. The assembly then was passed into the furnace and, after reaching the brazing temperature for the required time, was withdrawn from the furnace and cooled rapidly.

Keil, Hanks, and Taub[63] studied the brazing of beryllium and found that it is necessary to remove and exclude oxide films during joining operations. To accomplish this, they found it necessary to spray coat the beryllium. Prerequisites for obtaining good metal sprayed coatings are 1) the beryllium metal must be acid etched immediately prior to spraying and 2) the beryllium must be heated to 150°C (302°F). Good coatings were obtained with 1100 aluminum, a nickel chromium alloy, bronze, copper, an aluminum-12 % silicon alloy, a silver-30 wt % aluminum alloy, and pure silver.

Strong leakproof joints were made by induction brazing in a helium atmosphere using a titanium flux with the following brazing materials:

Silver copper eutectic alloy on silver plated or mechanically cleaned beryllium

Silver-copper eutectic containing 2.5 wt % zirconium on acid etched or silver plated beryllium

Pure silver on mechanically cleaned or acid etched beryllium

The joints produced with these brazing alloys showed highest strengths.

Furnace brazing, using a helium atmosphere and no flux, was only moderately successful with the following materials:

Pure silver

Silver-15 wt % copper, 16 wt % zinc, 24 wt % cadmium

Silver-30 wt % aluminum.

No difference was noted if the beryllium surface was mechanically cleaned or acid etched prior to brazing.

Induction brazing using magnesium on a magnesium coated surface without flux furnished a leakproof joint comparable in strength to the silver brazed joint.

Workers at Brush Beryllium Company[65] defined optimum conditions for silver brazing beryllium on the basis of tensile tests and metallographic and X-ray examination. They found that improved quality joints could be made in structural beryllium by brazing with pure silver at 900°C (1650°F, using a brazing time of 1 to 5 minutes and a pressure in excess of 40 psi. Starting with a very thin layer of silver, they found that closely controlling the brazing conditions increased the quality and reliability of the braze. Further improvement in the quality of the silver brazed joint resulted from heating at 600°C (1110° F) for times up to 1 week after brazing. This is shown in Table XXII.

These authors[65] further found that the tensile strength of butt brazed beryllium specimens, vacuum brazed at 900°C (1650°F) for 3 minutes in butted fixtures, was significantly higher in the as-brazed condition when a silver-05, wt % lithium braze alloy was used than with the following silver-base alloys: silver-2.3 wt % zinc, silver-0.16 wt % phosphorus, silver-0.20 wt % indium, silver-2.1 wt % tin, silver-0.30 wt % cadmium, silver-6.0 wt % germanium, silver-1.0 wt % silicon, and silver-5.6 wt % aluminum. The strength of beryllium specimens brazed with these various alloys is shown in Table XXIII. Silver rich brazing alloys containing highly volatile additions such as zinc, phosphorus, and lithium, produced higher tensile strengths in brazed joints than those containing relatively nonvolatile additions such as aluminum, silicon, tin, and germanium. The presence of the volatile additive appeared to improve the wetting and brazing of the beryllium.

Aluminum silicon brazing materials provide serviceable joint strengths of 20,000 to 30,000 psi up to 350°F.[59] Beyond this temperature, their strength rapidly deteriorates. Silver-base brazing alloys have essentially the same room temperature strength as the aluminum silicon alloys, but a strength above 25,000 psi can be maintained at 500°F and a strength of 10,000 psi at 1300°F. Thus, for high strengths at temperatures higher than room temperature, the silver-base braze alloys should be used.

Vickers[66] obtained successful joints in beryllium by brazing in vacuum. Metals and alloys that were used successfully as alloys for brazing were:

Silver-28 wt % copper

Pure silver

Silver-15 wt % lead, 20 wt % copper

Silver-5 wt % lead

Copper-18 wt % lead.

Table XXII. Summary of Tensile Test Data for Specimens Brazed* with Silver and then Heat Treated[65]

Heat Treatment Conditions		Testing Temperature (°C)	Ultimate** Strength as Brazed (10^3 psi)	Ultimate Strength (10^3 psi)	Strength (10^3 psi)
Temperature (°C)	Time at Temperature				
600	6 hr	RT	35.0	41.6	33.5
			31.0	41.3	33.6
			36.0	40.8	34.2
			Avg 34.0	41.2	33.8
600	1 wk	RT	34.0	39.8	32.4
			33.0	40.6	32.8
			35.0	39.8	32.7
			Avg 34.0	40.1	32.6
800	6 hr	RT	29.7	18.9	-
			29.5	15.0	-
			29.7	21.8	-
			Avg 29.7	18.6	
800	1 wk	RT	29.6	36.8	33.0
			29.7	22.5	-
			29.5	29.4	-
			29.7	41.4	33.1
			Avg 29.6	32.5	33.1
None	None	600	-	15.9	15.3
			-	15.8	15.7
			-	15.7	-
			Avg	15.8	15.5
600	6 hr	600	-	15.3	-
			-	14.5	-
			-	13.6	-
			Avg	14.5	
600	1 wk	600	-	12.5	-
			-	13.4	-
			-	15.6	-
			Avg	13.8	
None	None	800	-	6.3	-
			-	7.0	-
			-	3.1	-
			Avg	5.5	
800	6 hr	800	-	4.8	-
			-	5.5	-
			-	6.1	-
			-	5.1	-
			Avg	5.4	
800	1 wk	800	All samples broke in testing fixture		

* Beryllium specimens vacuum brazed at 900°C (1650°F) for 3 minutes prior to heat treating.

** Samples taken from positions adjacent to the heat-treated samples.

Table XXIII. Tensile Strength of Specimens Butt-Brazed* with Silver-Base Alloys[65]

Binary Addition	Addition (wt %)	Average Ultimate Tensile Strength (psi)
Lithium	0.5	41,200
		30,300
		32,000
		Avg 34,500
Zinc	2.3	13,400
		22,400
		27,600
		Avg 21,100
Phosphorus	0.16	20,100
		23,800
		18,700
		Avg 20,900
Indium	0.20	20,300
		14,400
		22,800
		Avg 19,200
Tin	2.1	16,600
		16,700
		Avg 16,700
Cadmium	0.30	26,500
		14,700
		9,400
		Avg 16,900
Germanium	6.0	10,900
		18,800
		15,400
		14,200
		Avg 14,800
Silicon	1.0	15,700
		8,200
		16,800
		Avg 13,600
Aluminum	5.6	4,400
		3,300
		Avg 3,900

* Beryllium specimens vacuum brazed at 900°C (1650°F) for 3 minutes and tested as brazed.

Interdiffusion of the brazing alloys with beryllium was evident after annealing for 1000 hours at 1112°F. Attempts to braze in argon, purified by passing over heated calcium chips, were not successful because oxidation of the beryllium occurred in the 1425° to 1825°F temperature range presumably caused by impurities in the argon.

Cline and O'Neill[67] studied beryllium brazements for use at service temperatures above 1000°F. They concluded that a silver-7.3 wt % copper, 0.2 wt % lithium braze alloy produced the highest strength at 1060°F for brazes made either in a vacuum or purified inert gas atmosphere. With silver-base brazing metal, the time above the eutectic temperature must be kept to a minimum to minimize the deterioration of the interface caused by intergranular penetration of silver in the beryllium. The quantity of voids found in the beryllium adjacent to the braze appear to be related to the time above the eutectic temperature. When heating the brazes by means of induction, care must be taken to prevent too rapid a heating rate, especially with larger brazements.

Maloof and Cohen[68] report that brazed butt joints, produced with pure silver or a silver-beryllium alloy, are approximately 60 percent as strong as the base metal at room temperature and 80 percent as strong as the base metal in the 700° to 1450°F range. Prolonged exposures at 700° to 1450°F did not affect the room temperature strength of joints brazed with a beryllium-20 wt % silver alloy. If a continuous silver interface in the joint is present, prolonged exposure at 1350°F or higher reduces the strength, probably because of formation of one or more compounds. Joints brazed with a beryllium-35 wt % silicon alloy were only about one-half as strong at room temperature as those brazed with silver or the beryllium silver alloy.

Solid state welding, also called self welding, pressure welding, and diffusion bonding, is a method for joining metals that avoids some of the difficulties involved in fusion welding processes.[69] It is especially valuable for joining beryllium that is to be used at elevated temperatures. Using vacuum hot-pressed block, specimens to be welded are placed in molybdenum clamps to hold the adjoining surfaces in contact while heating the assembly in vacuum at pressures of approximately 10^{-5} mm of mercury. Contact is maintained between the adjoining beryllium faces during heating because of the differential thermal expansion between molybdenum and beryllium with increasing temperature.

Weld strength was reported to depend on prior roughness of the adjoining surfaces, on welding temperature, and on base metal strength. Metallographically polished adjoining surfaces resulted in the most complete bonding. For such surfaces, the weld strength increased with increasing welding temperature up to 900° to 975°C (1650° to 1790°F). Above 975°C (1790°F), strength decreased because of grain growth in the base metal. Adjoining surfaces prepared by grinding on 180-grit paper required a bonding temperature of 1050°C (1925°F) to attain full bond strength. Chemical polishing and etching treatments of the surfaces to be joined must be avoided because a residual film remains at the interface and contributes to poor bonding.

Westlund[70] found that the use of silver as a brazing filler permits joining beryllium to titanium, beryllium to stainless steel, and beryllium to beryllium in vacuum. Brazing temperatures and times at temperature must be kept to a minimum to obtain highest joint strengths. He also reported that beryllium can be brazed to titanium or stainless steel at temperatures as low as 900°C (1652°F) which is 60°C (108°F) below the melting point of silver.

It was found[70] that the addition of a small amount of titanium hydride to the beryllium contact surface improved the wettability of the silver. High strength brazes were produced consistently at temperatures from 960° to 1070°C (1760° to 1958°F) showing that overheating was not a problem using this technique.

Based on exploratory investigation of the feasibility of resistance brazing of beryllium,[71] it was shown that beryllium spot brazing is capable of producing sound joints in 0.020-inch thick beryllium sheet using a silver-28 wt % copper eutectic filler alloy. The filler strip was 0.001 to 0.003 inch thick. Multiple brazing procedures showed no strength advantages over single brazing procedures. Additional work is required before a definite conclusion can be drawn as to the usefulness of this technique for joining beryllium sheet.

5. Welding

a. Solid State Welding

Maximum joint strengths produced by solid state welding were equal to those of the base beryllium metal, approximately 40,000 psi for hot-pressed block and 60,000 psi for extruded beryllium produced from hot-pressed block. Since the bond strength equals that of the base metal, the bonding process must involve attaining atomic contact across the interface, aided no doubt by localized plastic deformation and surface diffusion. The process appears limited to specimens of rather small size and to rather simple assemblies, because of the clamping requirements and because the clamped specimens must be heated in a relatively high vacuum.

Ultrasonic welding is another solid state process for joining metals without the aid of fluxes, solder, or filler metal.[72] The process consists of clamping the pieces to be joined at moderate static forces between an active sonotrode and an anvil. The anvil serves as a reaction element to the clamping force and the applied vibration. The tip of the active sonotrode is usually spherical, while the anvil face is usually flat. The equipment available (4 kw) limited the thickness of beryllium sheet that could be welded to approximately 0.020 inch.

Preliminary investigations indicated that the most satisfactory welds were obtained with beryllium sheet that was generally smooth, flat, and free of surface defects. Annealed sheet appeared to be more readily weldable than as-received sheet, although the extent of improvement was not established. Beryllium panels assembled from 0.010-inch sheet with ultrasonic spot welds on 0.75 inch centers indicated the feasibility of producing high quality beryllium bonds free from internal discontinuities.

The process in its present state of development does not appear to be ready for commercial use with beryllium sheet although it does have some promise for joining thin sheet. For joining sheet 0.060 inch and thicker, additional research with higher powered equipment will be required.

b. <u>Braze Welding</u>

A process intermediately between brazing and welding is braze welding. In this process, a groove, a fillet, a plug, or a slot weld is made using a filler metal having a melting point lower than that of the base metal but higher than 800°F.

Except where service temperatures or corrosion limits its usage, braze welding is employed using standard inert gas welding equipment and similar joint preparation methods.[73] The filler metal is an alloy compatible with beryllium but not beryllium itself. The arc plasma is used primarily as a heating source to allow the filler metal to wet and flow. This keeps melting of the beryllium to a minimum and produces a joint having essentially the same strength as the fusion welded base metal, but one with much greater ductility.

Best braze metal alloys are aluminum-12 or -5 wt % silicon and 99.9 wt % pure silver.[73, 74] For high temperature service, silver is generally used to obtain greater joint strength. The aluminum-12 wt % silicon alloy provides a braze metal deposit that is fairly resistant to corrosion and relatively free of porosity.[74] The aluminum-5 wt % silicon alloy also has been used with moderate success.

Some typical braze welding joints are shown in Figure 23. It can be seen that both butt and fillet braze welds are possible.[73] The back-braze welding technique is preferred when both sides of the sheet are accessible. For thin sheet, butt-braze welding is a desirable method of joining.

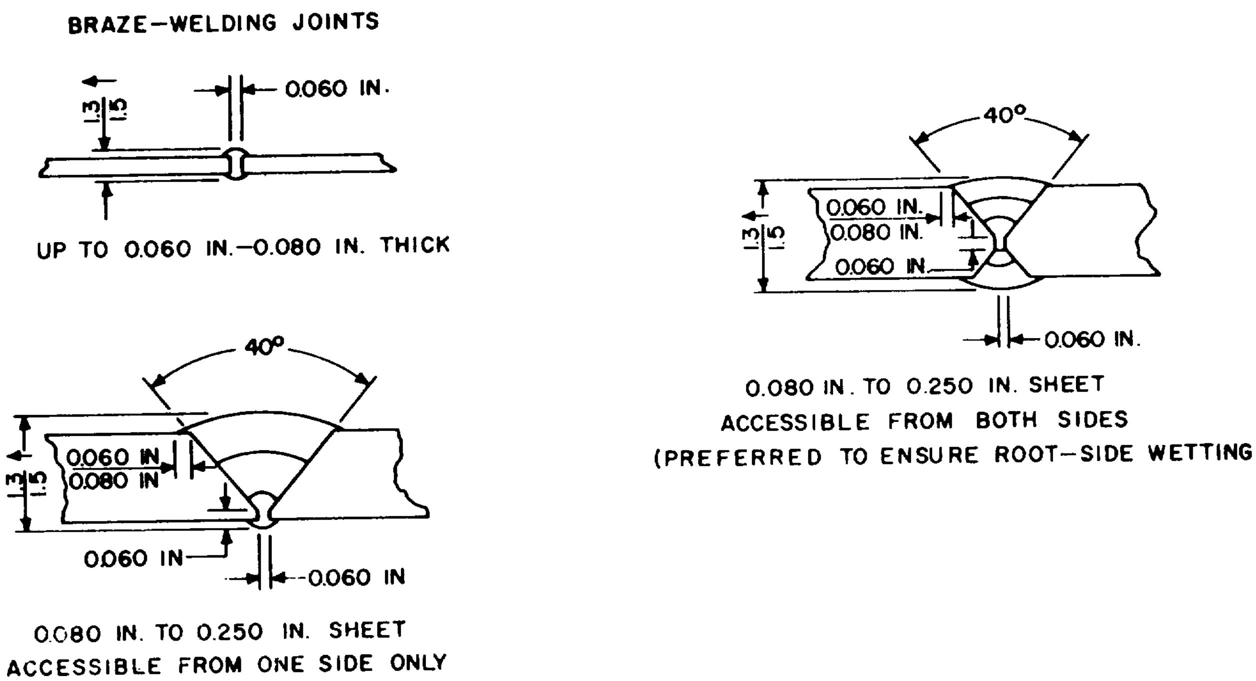

Figure 23. Typical Braze-Welding Joints[73]

The braze weld has the advantage over normal brazing in that sequential buildup of complex assemblies is possible. In addition, when furnace brazing with silver, the relatively high temperatures required adversely affect the desirable high mechanical properties of wrought beryllium. In braze welding, however, the heating is localized, often extending less than 0.060 inch beyond the braze metal base interface. Joint design can allow for this lowering of strength through localized reinforcement using the wrought properties of the metal to greatest advantage in the more highly loaded area.

Some porosity is encountered in braze welding beryllium with the aluminum alloy filler metals.[74] The porosity is more pronounced for multiple pass than for single pass applications. The porosity apparently results from release of hydrogen from the braze alloys. A pure helium shielding will help reduce, but will not completely eliminate, the accumulation of enough gas to form large pockets.

The metal arc and tungsten arc procedures yield butt welds with tensile strengths of 18,000 to 24,000 psi. The metal arc strengths are obtained with minimum joint preparations such as a 30-degree included "U" groove with a 0.030-inch root radius.

Basic metal and tungsten arc procedures are given in Tables XXIV and XXV, respectively. The tungsten arc techniques have the least tendency toward cracking.[74] Metal arc braze welds are performed on preheated assemblies. Preheats as low as 150°F are helpful, but temperatures up to 1000°F decrease the chances of cracking.

Commercial power supplies capable of delivering 300 to 500 amperes are available. These units are suitable for metal arc braze welding and should be equipped with internal inductance chokes that vary the amperage voltage characteristics needed to reestablish a short circuited arc. The equipment needed for tungsten arc braze welding includes a power supply capable of delivering ac or dc at 300 to 400 amperes. These needs are little more than are required for standard welding operations with the inert gas facilities.[74]

c. Fusion Welding

The increasing availability of sheet beryllium and fabricated shapes has led to successful developments in tungsten arc inert gas processes, metallic arc, and electron beam welding. However, most beryllium welding performed today utilizes the tungsten arc gas process.[59] The state-of-the-art has been developed sufficiently to provide consistently crack-free joints for weldments under 0.25-inch thick.[75] A method was described using the gas tungsten arc method with insulated fixtures of asbestos and coated graphite inside a plastic tent containing argon or helium. In addition to being cheap and flexible, large structures can be accommodated, and the welder has freedom of movement. Helium is usually preferred as a welding atmosphere. This development has shown that elaborate atmosphere chambers are not needed in welding beryllium. In fact, during automatic welding, sufficient protection against oxidation is provided by the shielding gas flowing from the welding torch in an open environment.

Table XXIV. Basic Metal-Arc Parameters for Braze Welding of Beryllium[74]

Procedure 1. Metal arc braze welds for high heat input conditions with aluminum 5 or 12 percent silicon alloys using direct current, electrode positive.

	A	B
Welding Current, amp	180-300	135-190
Voltage, v	Open: 38-40 Closed: 30-32	Open: 29-34 Closed: 24-26
Wire Dia (in.)	0.062	0.030
Wire Feed (in./min)	160-240	600-700
Wire Extension (in.)	3/8 - 3/4	5/16 - 3/8
Travel Speed (in./min)	25-50	35-80
Inert Gas (%)	85 He/15A	85 He/15A
Joint Fill (%)	120-150	120-150

Procedure 2. Metal arc braze welds for low heat input conditions with aluminum 5 or 12 percent silicon alloys using direct current, electrode positive.

	A	B
Welding Current (amp)	135-165	70-110
Voltage (v)	Open: 20-31 Closed: 20-23	Open: 22-24 Closed: 21-22
Wire Dia (in.)	0.030	0.020
Wire Feed (in./min)	500-700	800-1000
Wire Extension (in.)	1/4 - 5/16	3/16 - 5/16
Travel Speed (in./min)	80-120	80-110
Inert Gas (%)	85 He/15 A	85 He/15A
Joint Fill (%)	110-120	110-120

Procedure 3. Metal arc braze welds for applications with pure silver as the braze metal.

Welding Current (amp)	170-190
Voltage (v)	Open: 26-27 Closed: 23-24
Wire Dia (in.)	0.030
Wire Speed (in./min)	650-750
Wire Extension (in.)	3/4
Travel Speed (in./min)	60-100
Inert Gas (%)	100 A
Joint Fill (%)	120-150

Table XXV. Basic Tungsten-Arc Parameters for Automatic and Manual Braze Welding of Beryllium[74]

Procedure 1. Tungsten arc braze welds for manually applying 99.9 percent pure silver, aluminum 5 or 12 percent silicon alloys using an alternating current.

Welding Current (amp)	70-125
Voltage (v)	Open: 90 Closed: 28-32
Wire Dia (in.)	1/16 - 5/32
Wire Feed (in./min)	As required
Travel Speed (in./min)	As required
Inert Gas (%)	25 He/75 A
Electrode Type	Tungsten-2% thorium
Electrode Size (in.)	1/8 or 5/32
Preheat (°F)	1000

Procedure 2. Tungsten arc braze welds for automatically applying aluminum 12 percent silicon alloys using direct current, electrode positive.

Welding Current (amp)	40-75 amp
Voltage (v)	Open: 75-85 Closed: 30-35
Wire Dia (in.)	0.040-0.060
Wire Feed (in./min)	30-35
Travel Speed (in./min)	2-3
Inert Gas (%)	79 He/21 A
Electrode Type	Tungsten-2% zirconium
Electrode Size (in.)	1/8
Preheat (°F)	1000

The base metal should not be fused or seen by the tungsten arc. The arc must be directed towards the molten filler-metal puddle. The braze weld is made by preheating the parts to brazing temperatures with the tungsten arc. Heavy sections may require an additional outside heating to temperatures as high as 1000 °F. A small amount of filler material is then melted on the base-metal surface. The correct brazing temperature is reached when the molten puddle will "wet" ahead or alloy with the beryllium surface. The rate of progress depends on the action of the molten filler metal in "wetting" ahead of the arc.

Fusion welds of corner joints (90-degree angles) in sheets up to 0.125-inch thick are readily made using the tungsten arc process. Butt joints are made with slightly more difficulty because of the thermal expansion problems at this angle.

Mechanical properties of weldments depend strongly on grain size; fine grained structures are better at room temperature. Grains 40 to 60 microns in diameter have been obtained in 0.040- to 0.062-inch thick sheet, while slightly larger grains, approximately 80 microns, have been found in 0.125-inch thick sheet weldments. The strength of such welds varied from 25,000 psi for 0.250-inch sheet to 37,500 psi for 0.040-inch sheet, the elongation in 2.0 inches varying from 0.2 to 1.6 percent.

For sheets thicker than 0.040 inch, it is desirable to use beryllium welding wire to produce butt welds. Room temperature joint strengths over 40,000 psi have been produced with silver wire, and such filler wire is especially useful in joining beryllium to high temperature alloys or when thick sections are to be assembled.[75]

One problem involved in fusion welding is tearing and cracking. Passamore[76] reports that tearing and cracking tendencies during fusion welding are reduced by increasing preheat temperatures and by decreasing speed and current. Decreasing the size of the fusion zone as measured by penetration also decreases the tendency to tear and crack in the weld. Additions of aluminum to the fusion zone in amounts up to over 1 percent promote tearing, and the variability in the susceptibility to tearing encountered in various lots of beryllium has been attributed to variations in the aluminum content.

Wynne and Craik[77] found that cracking was reduced by decreasing the severity of the restraint and by increasing the speed of welding during electron beam melting. Introducing copper into the weld zone by preplating did not refine the grains in the weld zone. However, the use of a pulsed electron beam during vacuum welding resulted in finer grains.

One of the advantages of the electron beam welding process results from the very high depth to width ratio obtained in the molten zone.[59] Since the welding is done in a high vacuum, contamination is absent, minimizing problems of control encountered in some other methods. In addition, weldments possess a minimum width of heat affected zone and usually less distortion.

Unanimous opinions regarding the relative merits of the tungsten arc process versus the electron beam process for welding beryllium are lacking. McPherson and Beaver[75] report that although the weld structures obtained by the two methods were about the same, the many problems associated with making welds under high vacuum conditions make the electron beam process more expensive and less versatile than the tungsten arc process. Hess, et al., [78] on the other hand, state that electron beam welding overcomes some of the main causes of weld failure in beryllium. These causes include thermally induced stress cracking and excessive grain growth. However, they report that control of heat flow, chamber pressure, and weld energy input are necessary to successfully weld beryllium hot pressed and rolled sheet material. One obvious disadvantage of electron beam welding is the limitation in size of parts that can be welded, caused by the size of the welding chamber which must be evacuated to pressures of approximately 10^{-5} mm of mercury.

Kern and Lubin[79] studied the welding of beryllium and other alloys by electron beam techniques under an Air Force contract. They concluded that high quality welds are associated with the use of moderately high power density and low welding speed. This contradicts the opinions of Wynne and Craik[77] who recommend faster welding speeds to minimize cracking. At 1000°F, the strength of the welds was equivalent to that of the base metal. However, tensile and bend ductilities were lower than those of the base metal.

Malhomme and Thome[80] studied the welding of beryllium as it applied to closing beryllium cans containing fuel elements for nuclear reactors. Using Pechiney beryllium, they found less than 2 percent rejections with electron beam welding. Heliarc welding was found to be not as consistent, the rejection rate being approximately 20 percent. They also found that the presence of impurities and of chlorides, oxides, and carbides, often deliberately added to improve creep resistance of the beryllium, increased the difficulties during welding.

MacPherson and Beaver[81] found that the properties of beryllium fusion welds are improved by deformation by hot rolling under controlled conditions. The greater the reduction in thickness, the greater is the improvement in mechanical properties. Best weld microstructure was obtained by mechanically hot working the fusion weld reinforcement flush with the parent metal by roll planishing techniques. Hot working of the fusion-weld reinforcement is preferred over warm working. Reductions in thickness of 20 percent at 750°C (1400°F) yielded ultimate tensile strengths of over 50,000 psi.

d. Resistance Welding

Studies conducted by Jahnle[82] indicate that the cross-rolled beryllium sheet can be joined by resistance spot welding. Both preheating and postheating reduce the tendency for cracking by reducing residual stresses formed during cooling and altering the structure of the weld nugget. Resistance spot welding, however, has not been recommended for applications where strength considerations are important, except to keep the load-carrying beryllium members in proper location. Sticking of the copper electrode to the beryllium is a problem in spot welding beryllium. There are some indications that the tendency to stick is reduced by improved surface finish although this factor was not studied in detail.

Nippes, et al.,[83] investigated techniques for resistance spot welding of beryllium sheet in three thicknesses, 0.020, 0.040, and 0.060 inch. In general, their data agree with the observations of Jahnle[81] that preheating intervals that raise the temperature of the beryllium gradually to above 600°F, prior to welding, reduced cracking. Equally as important in minimizing cracking were postheat intervals that slowly cooled the weld from the melting temperature to approximately 600°F or below. The most effective means found for reducing the incidence of both weld porosity and cracking was the application of a forging force, 2.5 to 3.0 times the welding force, applied shortly after the completion of the weld interval. The time of application of the force appears rather critical since too short a delay in the welding force causes excessive indentation, and too long a delay fails to eliminate weld porosity.

MacPherson and Beaver[81] joined beryllium rod specimens, 0.625 inch in diameter, by resistance butt welding, using a close fitting alumina tube in the area of the weld. The use of this tube reduced the cooling rate and resulted in weld joints that were indistinguishable from the parent metal and had ultimate tensile strengths in excess of 45,000 psi. They also concluded that longer time at diffusion temperatures in the solid state diffusion range seem to promote more reliable joints.

If further information on joining beryllium is desired, see TM X-53453, The Fabrication of Beryllium - Volume VI: Joining Techniques for Beryllium Alloys.

SECTION IX. APPLICATIONS OF BERYLLIUM

Most of the applications of beryllium are due to the light weight of the metal, the ability of beryllium to absorb more heat per pound than any other material, and the high elastic modulus of the metal. The density of the metal is approximately 1.85 g/cc, the specific heat is 0.46, the melting point is 2345°F, and the elastic modulus is 4×10^7 psi. The ability to work the metal into useful shapes in recent years, in spite of the low ductility (especially in the short transverse direction) has been accomplished to a large extent by research investigations initiated and supported by various Government agencies. New applications for the metal, most of them in the aerospace effort, are being discovered almost daily.

In the sections that follow, a number of these applications are briefly discussed.

1. Inertial Guidance Systems Components

The dimensional stability and low density of beryllium make it ideally suited for inertial guidance system components. Most of the parts used for these applications are machined to close tolerances. Other characteristics which enhance the attractiveness of beryllium as an inertial guidance material are 1) high heat conductivity, which minimizes temperature gradients and the stresses resulting from uneven expansion, 2) a high modulus of elasticity which is essential for mechanical rigidity of the system, 3) a coefficient of expansion similar to motor and bearing materials, and 4) a high degree of isotropy in the conventional vacuum hot-pressed form.[84] The high elastic modulus of beryllium also imparts a high resonant frequency, increasing the sensitivity obtainable in instruments, such as accelerometers, that measure by an inertial mass.

For inertial guidance systems, minimum precision elastic limit values of 8000 psi have been established in specifications established by a number of organizations making or developing such systems. Current materials capable of meeting limits of 14,000 psi have been developed by at least one metal producer.[85]

2. Heat Sinks

The high specific heat, which increases markedly with increasing temperature, combined with high thermal conductivity and lightness makes beryllium attractive as a heat capacitor. The reentry surfaces of the Mercury capsules contain a beryllium heat shield 74 inches in diameter and 1 inch thick. The shield is forged at elevated temperature into a saucer shaped disk by means of a 50,000-ton press. Subsequent machining brings it down to its final shape. The finished weight of the shield is 350 pounds.[7]

Beryllium shingles, thin curved plates that protect the escape hatch and parachute enclosure on the Mercury capsule during flight, also have been fabricated of beryllium.[7] Nose cones for reentry bodies are another application for beryllium where its high specific heat makes it a most desirable material.[85]

Development work has indicated that a beryllium assembly for aircraft disk brakes is another potential application of beryllium.[85] Such an assembly can accommodate up to 1,500,000 foot-pounds (44,700 foot-pounds per square inch of lining area) in the same stopping time as a conventional steel disk brake having a maximum energy dissipation capacity of 425,000 foot-pounds or 12,600 foot-pounds per square inch of lining.[5]

The recently announced TFX fighter plane appears to be a likely candidate for a beryllium disk brake system. Some estimates have been made that up to 800 pounds of beryllium will be used in this plane.

3. Optical System Bases

Base supports for optical systems for aerospace use are another promising application of beryllium. The bases consist of cover plates of beryllium that are brazed to the face and back of a core of square shells machined from beryllium plate. The face plate is polished to produce an optical mirror. The good dimensional stability, high elastic modulus, low density, and low coefficient of expansion make beryllium attractive for this application.[85] Such mirrors have been machined in a variety of sizes ranging from approximately 1 inch to 96 inches in diameter. The most common sizes vary from approximately 10 inches to 24 inches in diameter. The silver 0.5 percent lithium braze is commonly used to braze the cover plates to the core. The mirrors are finished by optical polishing.[7]

These beryllium optical mirrors are for use in the "Goddard Experiment Package" (GEP), a telescope and optical system that will probe the stars for spectral data in the virtually unexplored ultraviolet range from 4000 to 1000 angstroms.[86] A 38-inch telescope will be put into space to obtain basic information on the stars. According to Edward Chin, project manager of GEP, "Without these mirrors, there might not be a GEP."

4. Rocket Fuel

The high heat of combustion of beryllium per unit weight of fuel, 17.2 kg-cal per gram, makes it second only to hydrogen.[85] This can be seen in Table XXVI where the heats of combustion of a number of metals are compared. This table shows that the most widely used solid propellant, aluminum, has a heat of combustion of only 7.4 kg-cal per gram of fuel. Both boron and lithium have heats of combustion higher than that of aluminum but lower than that of beryllium. On the basis of heat released per unit weight of fuel plus oxidizer (kcal per gram product), the superiority of beryllium over all other elements considered, including hydrogen, is evident by an impressive margin. This is shown in the last column of Table XXVI.

These various metals listed in Table XXVI can be compared for use in air-breathing engines and rockets by using heats of combustion in the seventh and eighth columns of the table, respectively. On the basis of the size of the numbers in these columns, beryllium ranks second only to hydrogen for use in air-breathing engines (column 7) and it ranks first for use in rockets (column 8). Additional data are available to support these conclusions.[87]

5. Missile Applications

Perhaps the production order for beryllium spacer assemblies amounting to over $2 million represents the most significant development in the history of beryllium towards its use as a standard structural material for aerospace vehicles.[88] Development by Avco, with the cooperation of Brush, of complex prototypes of the spacers for the Minuteman missiles, and the receipt by Brush of a quantity production order, are evidence that the forming limitations on beryllium's usefulness have been largely overcome. The position of the spacer in the overall Minuteman three-stage intercontinental ballistic missile is shown in Figure 24. Although it is one of the smaller components in the missile, the beryllium spacer will result in weight savings of more than 50 percent over its aluminum predecessor, thus increasing the range and payload of the missile.

Table XXVI. Heat of Combustion of elements in the First and Second Row of the Periodic Table[85]

Atomic No.	Element	Atomic (Molecular) Weight	Heat of Combustion (kg-cal/mole of product)	Product	Molecular Weight of Product	Fuel (kg-cal/g)	Product (kg-cal/g)
1	H_2	2	68.4	$H_2O(g)$	18	34.2	3.7
3	L_1	6.9	141.7	$Li_2O(s)$	29.8	10.3	4.75
4	Be	9.0	154.8	$BeO(s)$	25.0	17.2	6.2
5	B	10.8	280.0	$B_2O_3(s)$	69.6	13.0	4.0
6	C	12.0	94.4	CO_2 (g)	44.0	7.9	2.14
11	Na	23.0	99.1	$Na_2O(s)$	62.0	2.2	1.60
12	Mg	24.3	145.8	$MgO(s)$	40.3	6.0	3.6
13	Al	27.0	399.1	Al_2O_3	102.0	7.4	3.9
14	Si	28.1	201.3	SiO_2 (g)	60.1	7.2	3.54
15	P	31.0	365.8	P_2O_5 (s)	142.0	5.7	2.5
16	S	32.1	91.5	SO_3 (g)	80.1	2.85	1.14

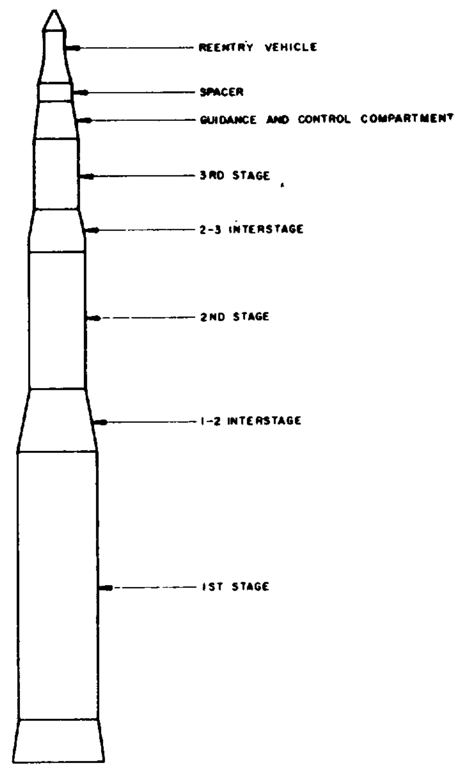

Figure 24. Minuteman Missile

The spacer (Figure 25) is a cylindrical beryllium shell, 32 inches in diameter and 11 inches high. It is fabricated by trepanning a heavy-wall ring from vacuum hot-pressed beryllium block and then ring rolling the shape to a thickness of 0.160 inch. Selected areas of the shell are chemically milled to reduce their thickness to 0.080 inch.

Load carrying structures in the assembly, called longerons, are formed from 0.055-inch thick beryllium sheet.[89] The longerons are brazed to the bulkhead with a low temperature zinc braze. Conventional riveting and adhesive bonding are used to attach the longerons to the shell. The position of the longerons in the assembly are shown in Figure 25.

Involved in the manufacturing of the spacer is the drilling of 276 holes in each spacer. Breakout in any of the holes would necessitate the scrapping of the entire part. By use of the electronically controlled Tornetic drilling unit, previously discussed, that controls both speed and feed rates, the holes in the spacer can be drilled without breakout and without resorting to the use of expensive backup drilling procedures.

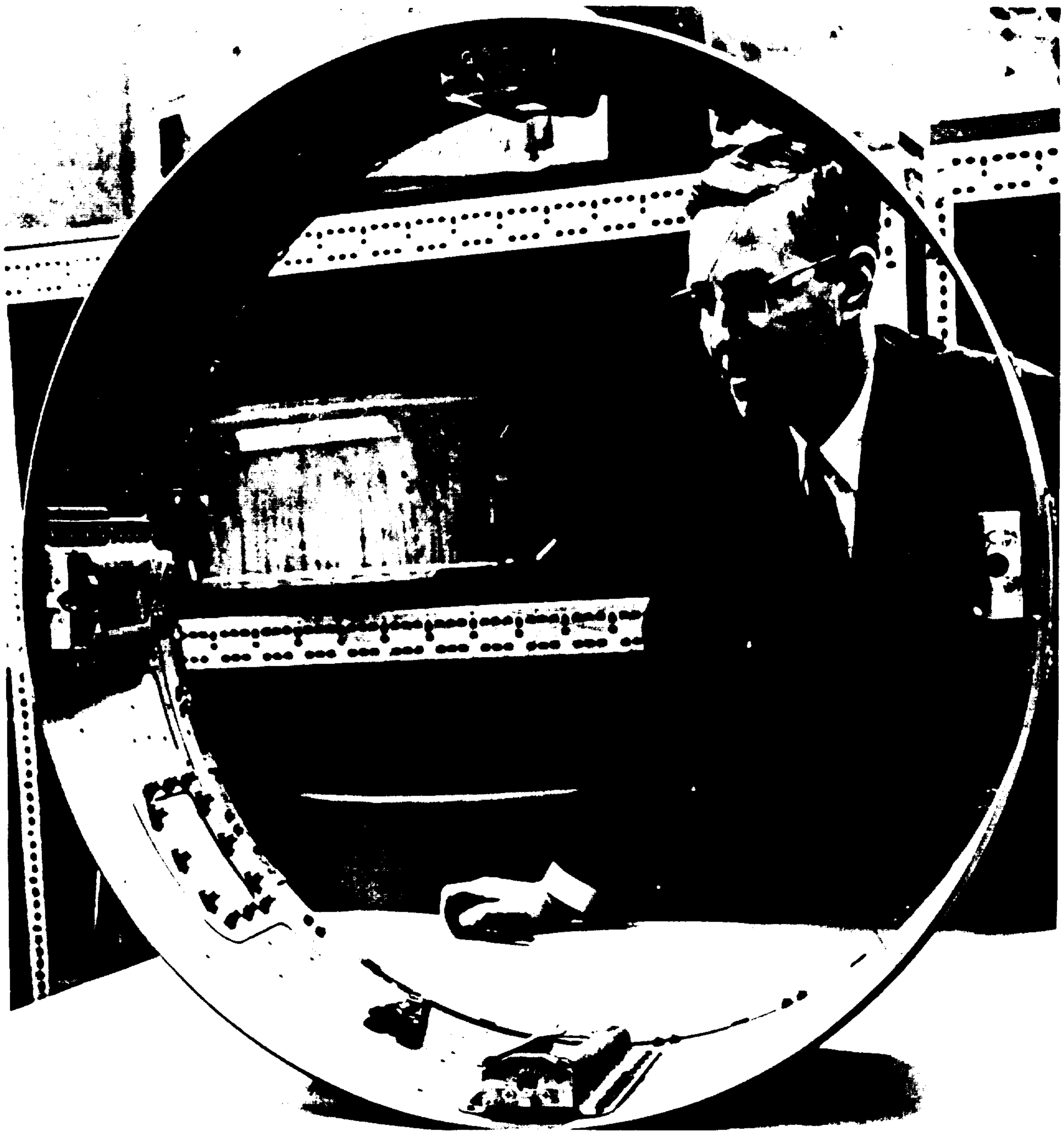

Figure 25. Overall View of Interior of Beryllium Spacer Assembly Showing Longerons in Place

Beryllium, in the form of vacuum hot-pressed block, has been used in several applications on the Polaris missile and to a limited degree on satellite programs. However, these were principally semi- or non-structural applications as weight-saving measures or where an elevated temperature environment was encountered. (Figure 26).

With basic engineering values now established and some fabrication experience achieved, there was sufficient basis for the decision to utilize beryllium cross-rolled sheet for forward rack panels and doors on the improved Agena vehicle.

This decision was part of an overall performance improvement program to increase the payload capability of the basic S-O1A spacecraft. The substitution of beryllium sheet for existing HM21A-T8 magnesium alloy provided a substantial weight reduction of nearly 20 lb. The segment involved is a right cylinder of 60 in. diameter and 40 in. height, composed of 18 panels mechanically fastened to existing HM31A-T5 magnesium structure by 1364 titanium (6Al-4V) screws and Cherrylock blind rivets (Figure 27). A general view of the forward rack assembly area is shown in Figure 28.

6. Guidance and Control Body Section

The recent fabrication and assembly of the two experimental guidance and control (CD-3) body sections for the Wing VI Minuteman missile is another example of the use of beryllium.[34] The design, development, and testing of these experimental sections was done by the Columbus Division of North American Aviation. The berryllium skins were made and joined mechanically to the aluminum frame structures by means of Cherrylock rivets at Brush Beryllium. To minimize cracking during assembly, adhesive shims were used between the frame and skins. Such shims are an epoxy adhesive identified as Epon 931. Static testing of this component met the design load criteria for Wing VI Minuteman. This component has the shape of a truncated cone, is 36 inches high, and has a major diameter of 36 inches and a minor diameter of 32 inches. Skin sections were chemically etched before and after drilling the more than 1250 holes so that the final skin section was 0.050-inch thick. Figure 12 shows an exterior view of the body and Figure 29 shows some of the interior details.

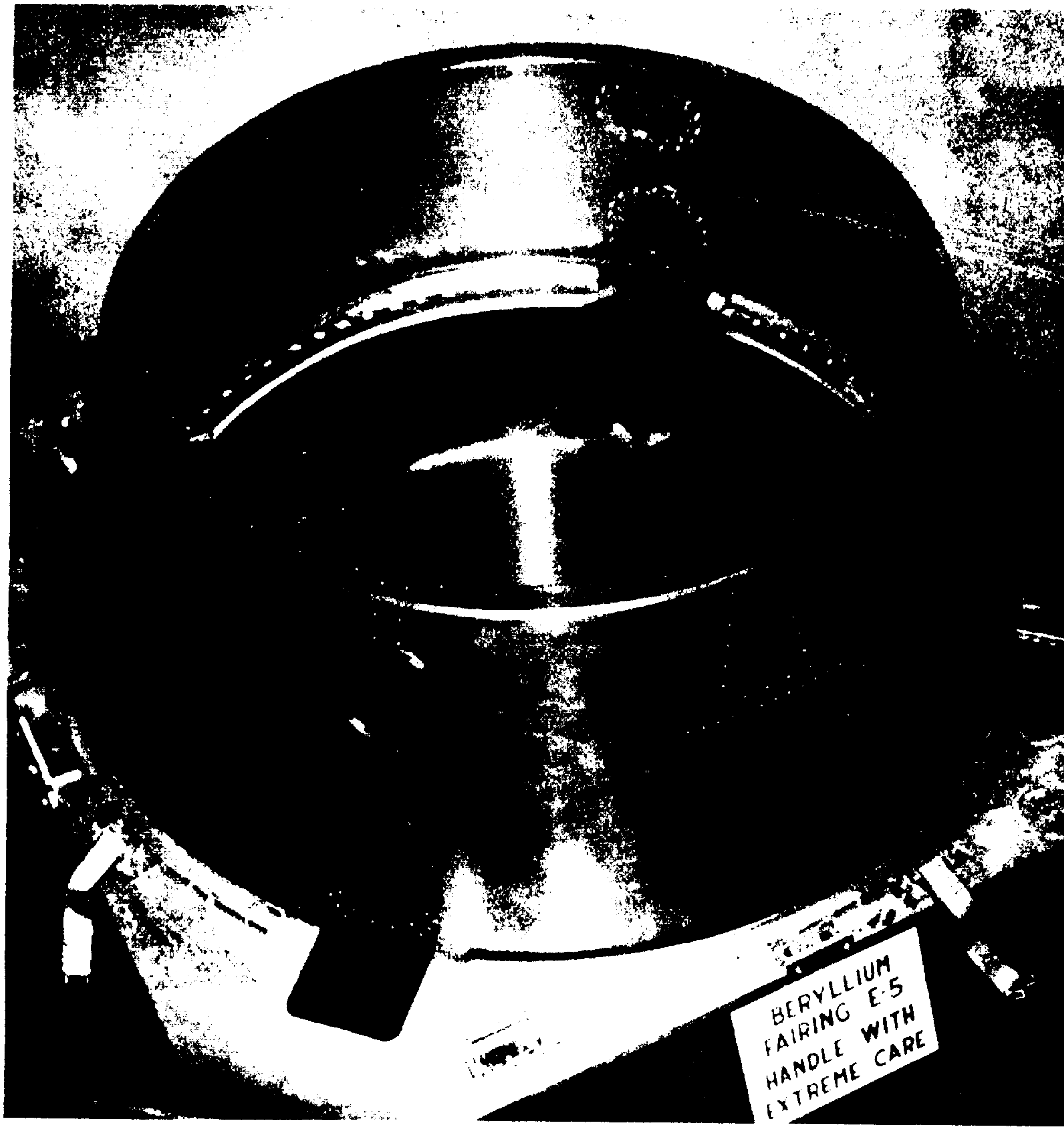

Figure 26. Large Truncated Cone Machined From 12,000-lb Vacuum Hot-Pressed Block

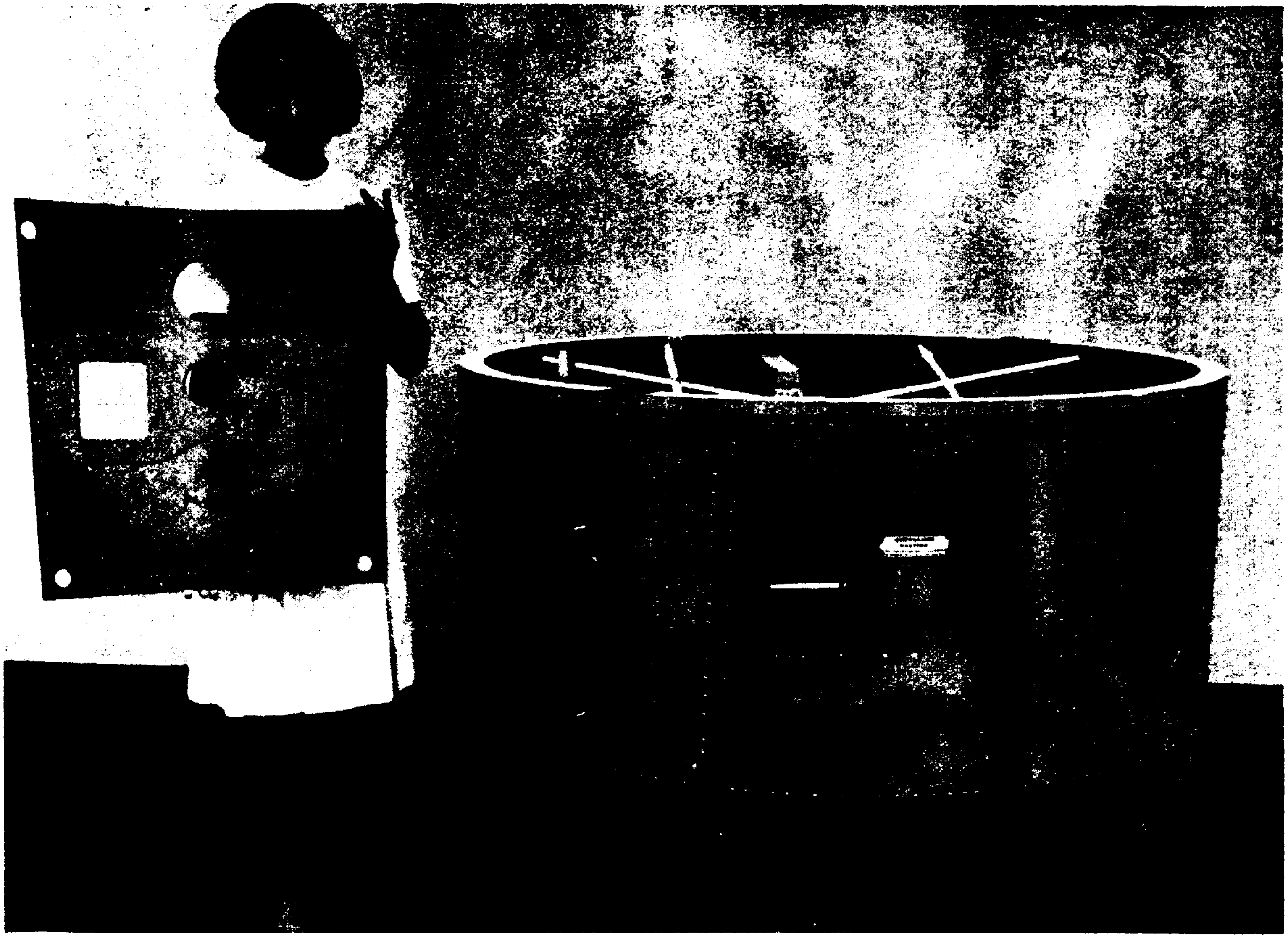

Figure 27. Completed Agena Forward Rack and Inside Surface of Chemical-Milled Panel

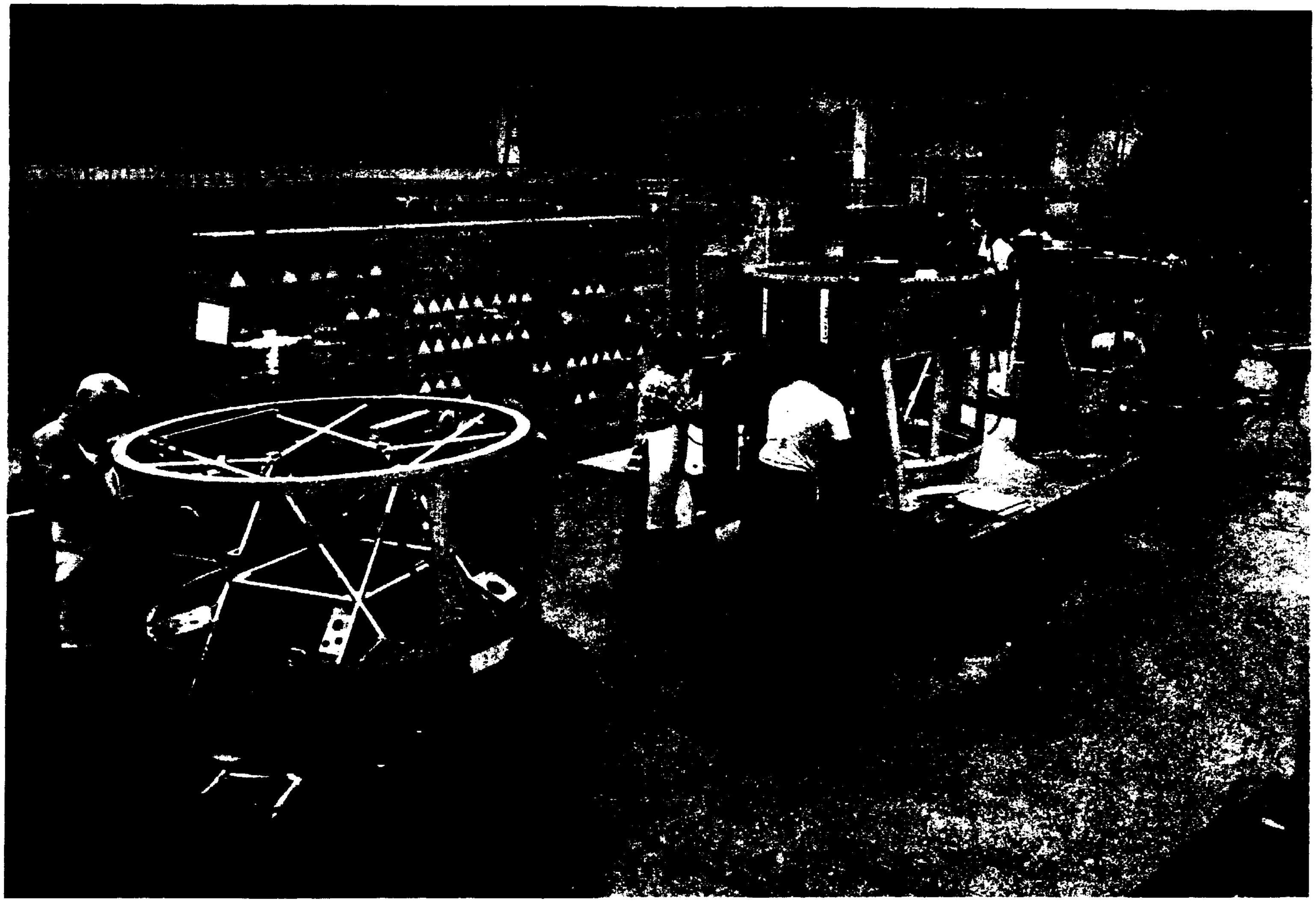

Figure 28. A Portion of the Forward Rack Final Assembly Area Showing Installed Beryllium Panels

Figure 29. Interior Details of Experimental Minuteman Guidance and and Control Body Section

7. Nuclear Applications

As early as 1951, beryllium was selected for use as a reflector or moderator in nuclear reactors, and this has been the major application of beryllium during the past [85]. The development of gas-cooled reactors has brought about the use of beryllium as the actual fuel container in the reactor. Here the moderating and reflecting qualities of beryllium and its reaction with beta particles to emit neutrons is of importance. The improved efficiency brought about by the use of beryllium permits the use of fuels with low enrichment. This contributes to reducing the costs of producing electrical power by nuclear reactors.

8. Antenna for Telstar

An antenna for the Telstar data gathering satellite being developed by the National Aeronautics and Space Administration is made of 0.099-inch diameter beryllium wire[7, 85]. Beryllium was chosen because of its light weight and stiffness. The antenna is designed to pick up signals in space for transmission to earth by means of Telstar.

The antenna was formed from 0.125-inch diameter extruded wire at room temperature using an intermediate stress relieving heat treatment. The units were assembled and attached to a brass feed through using a lead-34 wt % tin, 3 wt % zinc solder with a zinc chloride active flux. Care must be taken in such assemblies to ensure removal of the residual flux to prevent corrosion by galvanic action.

9. Structural Shapes and Composites

Honeycomb panels in which beryllium face sheets are brazed to honeycombs of various core materials also have been made and are being evaluated. Under an Air Force contract, the Defense Products Division of Aeronca Manufacturing Corporation, Middletown, Ohio, has made a study of techniques for producing the honeycomb structures[64,90]. Flat, curved, and double curved panels were constructed with maximum dimensions of 18 by 18 inches.

A variety of panels was fabricated consisting of the beryllium faced load bearing panels and porous ceramic heat shields developed to withstand temperatures in excess of 3000°F. Three basic porous ceramic forms were developed in the heat shield. These were alumina, zirconia, and silica. The heat shields demonstrated excellent resistance to severe thermal and dynamic loads provided by tests in the exhaust systems of turbojet and ramjet engines.

Fabrication methods and tooling for the beryllium-faced honeycomb structures include such processes as cutting, forming, chem milling, and brazing. The beryllium sheet face plates were brazed to a variety of superalloy and stainless steel honeycomb cores.

10. Jet Engine Applications

Recently, interest has been shown in using beryllium for parts to be used in jet engine compressors. For this application, the wrought and forged commercial beryllium, both the medium and high oxide metals (Berylco HP-20 and HPI-40, respectively) are being studied for direct application to compressor parts[91, 92]. The use of beryllium in compressor disks and shafting also is being investigated in addition to the blade application. The use of beryllium in these applications would result in the development of engines with higher thrust to weight ratios and higher operating efficiencies. This could significantly reduce takeoff gross weight of the aircraft and extend mission capabilities. Studies at one aircraft plant showed that the weight savings would be 42 percent if beryllium could be used instead of titanium for shafts, cases, and bolts, 60 percent in typical disk and blade assemblies in compressors, and approximately 50 percent in stators.

11. Miscellaneous Applications

Potential applications have appeared from time to time in the trade papers. Many of these applications are concerned with using beryllium sheet as a skin for various spacecraft. These applications are designed to take advantage of the light weight and rigidity of the metal in a manner similar to the use of beryllium for the Minuteman spacer. Two such applications are the use of curved panels of sheet beryllium for sections for the unmanned Agena D docking spacecraft [93, 94] and the potential use of beryllium as a meteoroid shield or bumper skin for spacecraft[95].

Another potential application for beryllium is the design, fabrication, and testing of spar components for aerospace vehicles[96]. This work, being done at the Aerospace Division of the Boeing Company, Seattle, Washington, includes the use of various metalworking operations such as forming, brazing, riveting, drilling, machining, and similar operations. Exhaustive tests are being used to select the fabrication methods likely to yield the best component.

King, et al.,[97] described a recent cooperative design evaluation program to develop beryllium into a reliable material for gas turbine components. In general, the data are encouraging. However, two major problem areas must be solved before beryllium can be used in this application. These were identified as impact strength and corrosion. Work is continuing on this investigation.

SECTION X. TOXICITY OF BERYLLIUM

There are some basic requirements for the maintenance of health and safety in facilities handling beryllium. The need for good house-keeping and sensible shop safety measures can offset, to a great extent, the hazards associated with working with beryllium.[98] However, the absolute necessity of keeping beryllium dust out of the atmosphere is a subject that can never be neglected in handling this material.

Elaborate safety measures are being taken to prevent dispersal of beryllium and its compounds into working areas. The Atomic Energy Commission has taken the position that "it is safest to regard beryllium and all its compounds as potentially toxic."[99] The paper by Breslin and Harris,[99] although published in 1958, is a good guide for use in handling the metal.

"Although there are hundreds of people alive and well today who worked with beryllium without any special precautions before its dangers were discovered, there are also several hundred cases of beryllium poisoning on record with an overall mortality rate of 23 percent."[100] "In many ways, human reaction to beryllium resembles an allergy in that many people seem to have no reaction to it, while a small percentage of the population may react fatally to microgram amounts of certain beryllium compounds. To date, no satisfactory way has been found to locate the hypersenstive individuals."[100]

Two forms of disease are known,[99] respiratory illness and certain kinds of skin reactions. The serious symptoms of berylliosis, the respiratory illness, are always the result of inhalation of beryllium compounds, especially the fluoride or sulfate. Inhalation of finely dispersed BeO can also lead to the disease. The mild form of reaction to beryllium, which occurs in sensitive individuals, is a contact dermatitis caused by handling beryllium and its compounds.[100] The resultant skin rash disappears when contact with the beryllium compound is discontinued.

Respiratory illness appears in both an acute and a chronic form.[99] The acute form has been found only among industrial workers; the chronic form reportedly occurs both among industrial workers and nearby residents.

The Atomic Energy Commission has established maximum allowable atmospheric concentrations of 2 micrograms per cubic meter averaged over an 8-hour day and 25 micrograms per cubic meter as the maximum which may not be exceeded even for a short time.[99] These are the same as those adopted by the United Kingdom Atomic Energy Authority.[101] No cases of berylliosis have occurred where these limits were met.[100] These limits can be met only by scrupulous cleanliness and by the provision of very effective ventilation systems for collecting all dust generated by processing beryllium. In addition, close medical inspection and supervision of personnel is necessary. The many plants successfully working with beryllium are proof that these conditions can be met in practice.

Practical general suggestions for working with beryllium might include the following:[102]

Equipment and other surfaces on which dust may collect must be cleaned thoroughly and frequently. Use of smooth surfaces covered with glossy paint assists in such cleaning.[98]

Vacuum cleaning is the preferred procedure for removing beryllium dust from equipment and other plant areas. Central or movable vacuum equipment may be used, but air passing through such equipment must not be discharged into the work area.[102]

Dry sweeping and the use of compressed air for blowing dust from any surface must be avoided.[102]

Damp cloths must be used for wiping surfaces that cannot be adequately cleaned by vacuum.[102]

Streams of water should not be used in open work areas since they disperse contaminated mists or spray into air, particularly if working pressure is high.[102]

For machining operations,[102] every machine should be equipped with a special vacuum line near the tool for evacuating air at velocities usually ranging from 500 to 3000 feet per minute[102] although the use of air velocities as high as 6000 feet per minute have been reported.[98] In all cases, the hood or suction line should be located so that the moving air is directed away from the machine operator toward exhaust openings. The more hazardous beryllium machining operations such as grinding, ball milling, and similar operations, that produce fine dust particles, must be performed in hooded machines equipped with adequate suction facilities. In some cases, special shape orifices can increase efficiency of dust and fume collection. The dust should be carried to a suitable separator after passing through a cleaning system. The separator provides a means of reclaiming chips. Personnel working in an area where beryllium is machined are generally provided with uniforms so that they won't pick up beryllium on their own clothes.[98] A locker room within the area is available for changing into and out of the uniforms. Floor-level rotating shoe cleaners automatically wipe the shoes of personnel leaving the area so that no beryllium can be tracked out.

In general, respirators should be used only for short periods of exposure to concentrations of beryllium below 100 milligrams per cubic meter of air.[102] Air supplied to self-containing respirators should be used for prolonged or continuous work in atmospheres containing beryllium concentrations in excess of 100 micrograms per cubic meter of air.

Periodic sampling and analysis of plant atmosphere should be accomplished on a regular scheduled basis.[102] Samples collected at the normal breathing levels of plant personnel are most significant. Frequency of sampling and the number of samples to be collected at each work location, and in the general work area, must be carefully determined so that the daily weighted average exposure for each individual may be estimated with accuracy.

Some machining operations such as milling, broaching, and rotary and bandsawing operations require the use of cutting fluids in addition to local exhaust ventilation to minimize dispersal of dusts.[102] In such cases, provision must be made to collect the contaminated mists and sprays. When no longer useful, contaminated, insoluble cutting fluids should be filtered to remove the beryllium particles and then disposed by burial or burning under supervised conditions. Water soluble cutting oil may be discharged directly into industrial waste systems after filtering or standing for a sufficiently long time to allow all of the beryllium particles to settle out of the liquid.

Solid wastes such as wiping rags, contaminated filter papers, sludges, and dusts collected by vacuum cleaning systems and air cleaners, require special care.[102] In some cases they can be burned; in others, special procedures must be arranged.

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This document has also been reviewed and approved for technical accuracy.

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