DMIC

FABRICATION

Joining. Bogowitz and Metcalfe have studied the brazing of beryllium by capillary flow at Solar.(1) Four silver-base alloys were developed that show improved flow. Titanium-base braze alloys were shown to wet better than any silver-base alloy, but optimization of these alloys was not possible on this program. Evaluation procedures included flow on flat beryllium sheet, capillary flow over a vertical distance of 1 inch during heating, vertical capillary flow at selected temperatures versus time, structures, and strength and stability of brazed joints. Brazing temperatures below 1550 F are desired because of degradation of properties in beryllium sheet at high temperatures. The comparative results of these studies for the silver-base alloys in an argon atmosphere are presented in Table 1. The recommended compositions are indicated and their braze temperatures given.

Machinability. As part of a combined U. S. Air Force and U. K. Ministry of Aviation cooperative research and development program, General Electric attempted to establish base lines for the use of beryllium in turbine-engine components. As Part II of the program, machinability was studied during the period, March to November, 1965, after which the program was redirected. Results of the study were summarized by Glynn and Bayer.(2)

The two machining methods that showed the most promise for processing beryllium are (1) conventional machining followed by chemical etch and (2) electrochemical machining. The advantages of conventional machining are a high rate of stock removal, use of conventional tooling practices, and the ability to remove the surface damage by an inexpensive chemical treatment; the advantages of electrochemical machining are tenable metal removal rates, very good surface finishes, no metallurgical damage to the beryllium, and no requied posttreatment. Machinability data for conventional machining presented in Table 2 and Figure 1 represent an experimental verification of previously accepted procedures.

Electrochemical machining was accomplished using an electrolyte consisting of 4 pounds of $NaNO_3$ per gallon of water at 100 F. The process constants were determined to be a metal removal rate of 11.6 x 10^{-3} cu in/amp-min and a starting voltage of 4.5 volts, with a specific resistance of 4.19 ohm-cm in fully aged electrolyte. Satisfactory surface finishes (50 microinches) and practical metal-removal rates can be expected for this ECM system when cutting under steady-state conditions. Operating conditions determined necessary for this process were working gaps of 0.008 to 0.020 inch, feed rates of 0.020 to 0.100 inch per minute, and an electrolyte velocity of 30 to 110 feet per second. Machining conditions chosen should not be a combination of the three lowest operating conditions.

Sheet Formability. Lockheed has investigated the production techniques required for the severe forming of commercially available cross-rolled beryllium sheet.(3) Although large-radius, simply curved panels are being formed and machined on a routine production basis for both Agena and Gemini spacecraft, the limited knowledge of suitable production techniques and experience in forming complex shapes is still a deterent to a general adoption of cross-rolled beryllium sheet for primary aerospace structures. Therefore, this work was directed toward the development of both engineering and production information on the forming of simple and complex configurations. Examples of (1) straight bends are angles, channels, Zee sections and hat sections; of (2) complex curvatures are spherical segments, channel ring segments, and closed-end semicylinders and of (3) joggles are angles.

The forming dies were made of Glassrock[a] (a ceramic with very stable thermal characteristics) with 11- or 14-gage NICHROME[b] wire heating elements 1/2 inch apart and imbedded 1/2 inch from the working surface.

Initial experimentation was carried out on straight bends to determine the minimum bend radius-to-thickness ratio and the optimum forming temperature. Radii of 4, 5, and 6t at temperatures of 1050, 1250, and 1350 F were investigated. The resulting data indicated a minimum bend radius of 5t and an optimum forming temperature of 1350 F. These restrictions or parameters were used for the subsequent forming operation.

For the more complex straight bends, the folding-action die approach results in less material stress at the bend radius and eliminates specimen galling due to material movement across the die. This is preferred to the punch-and-die approach when practicable.

For compound curves, 9 to 13 percent shrink and stretch values were determined to be feasible if tool drag is eliminated. Joggling of beryllium angles is entirely feasible if nominal transition lengths of 10t and joggle depths of 3t are utilized. In all cases, temperature distribution in tool and workpiece is critical if distortion is to be avoided.

(a) Registered trademark of the Glassrock Products Company.
(b) Registered trademark of the Driver-Harris Company.

TABLE 1. COMPARATIVE REVIEW FOR CANDIDATE ALLOYS(1)(a)

	Tolerance		Braze Characteristics		Interaction	Mechanical Strength	
Braze Alloy	Atmosphere (Ti/Be Spacer)	Surface Condition (Etch Depth)	Capillary Flow(b)	Braze Temperature	Beryllide Thickness(b)	Joint Shear	Beryllium Tensile
Ag-Cu-Li (6)	2	2	3	2	3	3	2
Ag-Cu-Ti (6B1)	1	2	3	3	4	2	2
Ag-Cu-Be-(6C)	1	2	3	3	4	2	2
Ag-Cu-In-Ti (6H5)	4	2	2	3	3	2	1
Ag-Cu-Ge (6J)	4	1	1	2	1	2	2
Ag-Cu-Ge-Ti (6J5)	3	2	2	3	2	2	-
Ag-Cu-Mn-Ge (6K6)	4	1	3	3	4	3	2
Ag-Cu-Mn-Ti (6K7)	2	2	3	1	5	1	1
Ag-Cu-Mn (6K9)	2	2	3	1	4	3	3
Ag-Cu-Mn-Ge-Ti (6K13)	2	2	3	3	5	3	3

Parameter Basis For Award of Points

Temperature Change for 0.5 In. Flow		Flow Increase on Flat Plate		Vertical Flow		Based on Preferred Temperature at 1550 F(c)		Beryllide at Interface		Shear Strength		Base Metal Strength	
Points	Change, F	Points	Flow, %	Points	Flow, in.	Points	Temp, F	Points	In. x 10^{-4}	Points	Strength, psi	Points	Strength, psi
1 =	>150	1 =	>20	1 =	<0.5	1 =	>1650	1 =	>10	1 =	<10,000	1 =	<40,000
2 =	>100 <150	2 =	<20	2 =	0.5-0.75	2 =	1551-1650	2 =	5-10	2 =	10,000 to 13,000	2 =	40,000 to 50,000
3 =	>50 <100			3 =	0.75-1.0	3 =	<1551	3 =	2-5	3 =	>13,000	3 =	>50,000
								4 =	1-2				
								5 =	<1				

(a) For argon atmosphere.
(b) 10 minute braze.
(c) Higher temperatures anneal out the desired structures.

Note: The recommended braze temperatures and compositions are 1550 for Ag-12.5Cu-5Mn-1Ge-1Ti, Ag-12.5Cu-5Mn-1Ge, and Ag-12.5Cu-1Li; 1650 F for Ag-7.5Cu-15Mn.

Lockalloy. A study of weight saving for Saturn-type vehicle structures by substituting beryllium-aluminum alloys for aluminum was made by Armstrong and Whitfield at Lockheed's Huntsville Research and Engineering Center.(4) The main materials studied were aluminum, beryllium-38aluminum, and beryllium. In addition to these materials, magnesium-lithium (LA 141), magnesium-thorium (HK 31A-H24), and titanium (Ti-6Al-4V) alloys were also studied. Cylindrical configurations with three types of stiffeners were studied. These were rectangular rings and stringers, trapezoidal corrugations and angle-section rings, and flanged stiffeners and rings. These studies showed that structures of the beryllium-aluminum alloy optimize at approximately 50 percent of the weight of aluminum structures for application in current Saturn upper-stage structures. More heavily loaded structures show smaller weight savings (30 percent), but are still significant in view of the cost per pound of orbital and escape payload weight. A cost study showed the cost saved per pound to be reasonable, indicating that immediate consideration of beryllium-aluminum alloys for primary structures is warranted. The significant data are summarized in Tables 3 and 4. Digital computer programs used in this study for preliminary structural design produced useful stress, weight, and configuration details to a depth not heretofore available.

PHYSICAL METALLURGY

Splat-Cooled 4 Percent Copper. Kaufman is studying splat cooling as a means to produce fine-grained beryllium, unalllyed SR beryllium, and a 4-percent copper alloy at Nuclear Metals Division of Whittaker Corporation.(5) In the consolidation process used, the powder is vacuum hot pressed followed by rolling or extruding. Tensile testing of the extruded splat material produced yield strengths of 50,000 to 77,000 psi and ultimate strengths of 50,000 to 97,000 psi. Although low for the unalloyed material, elongation of the copper alloy was as high as 6 percent. All samples except those which were completely brittle showed well-defined yield points and frequently had a drop in load after yielding. Many of the 4 percent copper samples also had a period of easy glide following yielding. A Cottrell effect, in which impurity atoms lock the dislocations up to the yield point, was possibly the cause. Apparently, the impurity causing the yield-point phenomenon tends to inhibit fracture on the 1120 plane, therefore, strengthening the material. Generally, the splat source materials are more resistant to plastic deformation at 600 to 900 C (1110 to 1650 F) than ordinary hot pressed powder. This may be due to the fine grain size and unusual morphology or to incomplete bonding that would prevent plasticity across powder particle boundaries.

TABLE 2. RECOMMENDED MACHINING PRACTICES[2]

Rough Turning[a]

Speed:	75 to 150 sfpm
Feed:	0.010 to 0.015 inch/revolution
Depth:	0/060 to 0.120 inch
Geometry:	Positive Rake 0 to 45 degree Side Cutting Edge Angle 0.03 Nose Radius
Grade:	Class C-2 (94WC-6Co)
Fluid:	Oil; no chlorine or sulphur

Finish Turning[b]

Speed:	150 to 300 sfpm
Feed:	0.005 inch/revolution
Depth:	0.005 inch
Geometry:	See Figure 1[c]
Grade:	Class C-2 (94WC-6Co)
Fluid:	Oil; no chlorine or sulphur

(a) High speeds are possible when chip evacuation is controlled.
Final pass should be made at 0.010-inch depth of cut in order to minimize surface damage. Negative rake geometry is applicable and represents greater economy in tool costs.
(b) The last three passes across the work-piece should be made at 0.010, 0.005, and 0.005-inch depth of cut, respectively, to maintain the highest quality surfaces.
(c) Figure 1 illustrates the high positive rake tool geometry used in tests 22, 23, 24, and 29, which produced the most damage-free surface.

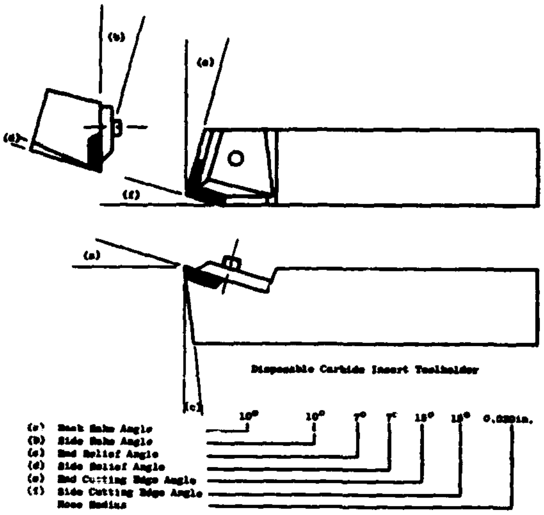

FIGURE 1. BERYLLIUM TURNING TOOL--HIGH RAKE GEOMETRY.[2]

TABLE 3. COST PER POUND OF WEIGHT SAVED: Z STIFFENED CYLINDERS 260-INCH DIAMETER x 36 INCHES LONG[4]

Material	Weight, pounds	Weight Saved Compared to Aluminum, pounds	Cost Each (lots of 10), dollars	Increased Cost Compared to Aluminum, dollars	Cost per Pound of Weight Saved, dollars/pound
Al	209.3	0	13,200	0	0
Be-Al	98.6	110.7	40,000[b]	26,800	242
Be	74.7	134.6	52,140	38,940	286
Composite[a]	144.0	65.3	38,500[c]	25,300	388

(a) Aluminum skin, beryllium-aluminum-stringers.
(b) Adjusted for less material.
(c) Adjusted for no ring.

TABLE 4. NET COST SAVINGS PER LAUNCH FOR ORBITAL PAYLOAD UNIT WEIGHT[4]
(Based on $1,000 Per Pound Payload Cost)

Material	Weight Saved, pounds	Gross Cost Saving, dollars	Increased Hardware Cost,[b] dollars	Net Cost Saving/Launch, dollars
Be	134.6	134,000	38,940	95,060
Be-Al	110.7	110,700	26,800	83,900
Composite[a]	65.3	65,300	25,300	40,000
Al	0	0	0	0

(a) Aluminum skin, beryllium-aluminum stringers.
(b) See Table 3.

Copper Alloyed Ingot Sheet. The Beryllium Corporation has been engaged in an investigation of solid-solution strengthened, high-purity beryllium alloy sheet.[6] The alloy compositions being studied contain 0.008, 1.0, 2.79, and 4.65 percent copper. Ingots of these alloys have been extruded into slabs and rolled at 1000, 1200, and 1400 F yielding approximately 0.05-inch-thick sheet. An equiaxed average grain size of about 43 microns has been produced by annealing 1 hour at 1300 F subsequent to rolling. Although formability and property characterizations have not been completed, the 0.008 percent copper alloy has exhibited superior forming characteristics as compared to the 1.0 percent copper alloy, and both the 0.008 and 1.0 percent copper alloys have shown the most attractive elevated-temperature elongation as compared to the 2.79 and 4.65 percent copper alloys.

MECHANICAL METALLURGY

Anisotropy. North American Aviation has investigated the effects of forging variables on anisotropy in beryllium forgings.[7] Combinations of uniaxial forging by extrusion and biaxial forging by upsetting against the extrusion direction were studied for their effects on anisotropy. Properties measured were orientation, microstructure, strength, and thermal expansion. The results of this investigation are expected to suggest forging practices for the production of relatively isotropic beryllium forgings.

The initial experiments indicated that upset-forging reductions ranging from 45 to 60 percent could minimize the anisotropy of material extruded at ratios ranging from 4 to 7. The preferred-orientation and mechanical-property data indicated that reasonably isotropic hot-pressed beryllium can be made anisotropic through uniaxial forging and can then be made much less anisotropic through subsequent biaxial forging 90 degrees opposed from the uniaxial direction. The thermal-expansion data showed a similar trend where the degree of anisotropy of upset-forged beryllium was 1.14×10^{-6} per F while the extruded and upset-forged material had only 0.330 and 0.422×10^{-6} per F. Decreasing the forging temperature from 1350 to 1250 F increased the yield strength and ductility by modest amounts. Increasing the stress relief temperature from 1250 to 1420 F decreased the yield strength and the yield anisotropy, but had no effect on ultimate tensile strength and elongation. This analysis has been vague because of the widely scattered data. Since it has been argued that a given process will produce the same degree of anistropy on the average, this scatter in data is interpreted as an indication of large point-to-point variability within a specimen.

OXIDATION PROTECTION

The protection of beryllium from high-temperature oxidation by use of a chromate film was the objective of an investigation at Frankford Arsenal.[8] The presence of chromium ions in the chromic acid anodic coating has been considered to be an important factor contributing to the resistance to oxidation of this coating. The introduction of higher valency chromium ions in the beryllium oxide lattice could be expected to diminish the concentration of excess beryllium ions in the oxide structure, thereby suppressing the transport of beryllium ions in the oxide coating to retard oxidation. The chromate film was applied from a proprietary (U.S. Patent 2796371) chromating solution normally used for aluminum. The specimens were 1.3-cm-diameter by 1.3-cm-long cylinders of hot-pressed, extruded, and machined beryllium and were chromated at 25 C for 30 minutes. As illustrated in Figure 2, chromated beryllium was unoxidized after 24 hours of exposure to moist air at 900 C (1652 F), while untreated beryllium was catastrophically oxidized under the same conditions.

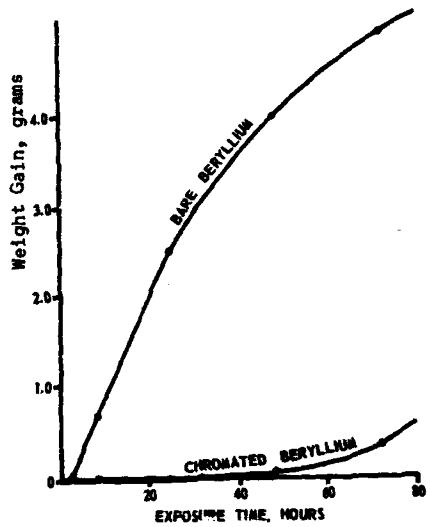

FIGURE 2. OXIDATION OF BARE AND CHROMATED BERYLLIUM IN MOIST AIR AT 900 C (1652 F)[8]

NEW CONTRACTS

Wire. An investigation has been initiated at Value Engineering Company to develop and fully characterize a manufacturing method for surface finishing drawn beryllium wire to produce a wire with a smooth surface, increased strength properties, and improved formability characteristics.[9] A process has been developed that uses electrochemical etching and ultrasonic energy to remove the nickel from the wire. Chemical milling in conjunction with ultrasonics imparts a smooth finish to the wire surface. The mechanical properties of the as-received, nickel-clad beryllium wire are presented in Table 5. Although this material has not yet been fully characterized, a definite increase in the bend ductility of the beryllium wire was observed after surface finishing.

Mechanical Metallurgy. Armstrong, Richman, and Gurland have recently begun an investigation of the internal structural factors determining the flow and fracture strengths of beryllium.[10] Their approach will cover the following three areas: (1) to assess quantitatively the applicability of an analysis to specify a hypothetical ductile-brittle transition temperature for beryllium by

TABLE 5. MECHANICAL PROPERTIES OF NICKEL-CLAD BERYLLIUM WIRE[9]

Wire Diameter, inch	0.0058	0.0056	0.0057	0.0057
Nickel Thickness, inch	0.00035	0.00030	0.00040	0.00035
Tensile Data				
Ultimate tensile, 10^3 psi	177	162	152	172
Yield strength, 10^3 psi	156	139	139	151
Modulus, 10^6 psi	28.1	30.9	30.0	24.4
Elongation, percent	1.4	1.0	1.3	1.4
Bend Ductility				
Minimum diameter around which wire passed, inch	0.0700	0.0700	0.0700	0.0700
Maximum diameter around which wire failed, inch	0.670	0.0670	0.0670	0.0670

equating the Hall-Petch stress-grain size equations for plastic yielding and tensile fracture; (2) to investigate the usefulness of hardness measurements in the study of cracking and their correlation with yield and tensile stress measurements; (3) to study the interrupted propagation of cracks in bend testing by the replication procedure.

REFERENCES

(1) Bogowitz, R. G., and Metcalfe, A. G., "Brazing Beryllium by Capillary Flow", Final Report AFML-TR-67-14, International Harvester Company, Solar Division, San Diego, Calif., Contract AF 33(615)-2853 (January, 1967) DMIC No. 67704.

(2) Glynn, C. E., and Boyer, J., "Machinability of Beryllium", Report AFML-TR-66-125, General Electric Company, Cincinnati, O., Contract AF 33(615)-2241 (October, 1966) DMIC No. 65804.

(3) Ingels, S. E., "Ductility of Cross-Rolled Beryllium Sheet - Barrier or Challenge", Report LSMC-A820503, Lockheed Missiles and Space Company, Sunnyvale, Calif., Contract NAS 8-11798 (March 15, 1966) DMIC No. 67496.

(4) Armstrong, H. H., and Whitfield, M. L., "Weight-Saving Through Use of Beryllium-Aluminum Alloys for Saturn-Type Vehicle Structures", Final Report CR-74788, Lockheed Missiles and Space Company, Huntsville, Ala., Contract NAS 8-11298 (March, 1966) DMIC No. 66901.

(5) Preliminary information reported by Nuclear Metals Division of Whittaker Corporation, West Concord, Mass., under U. S. Navy Contract NOw-66-0170-c.

(6) Preliminary information reported by The Beryllium Corporation, Reading, Pa., under U. S. Navy Contract NOw-66-0563-c.

(7) Gross, A. G., and Colteryahn, L. E., "Effects of Thermal-Mechanical Variables on the Anisotropy of Forged Beryllium", Report AFML-TR-66-333, Autonetics Division of North American Aviation, Inc., Anaheim, Calif., Contract AF 33(615)-1677 (December, 1966) DMIC No. 66898.

(8) Pearlstein, F., Wick, R. W., and Gallaccio, A., "Protection of Beryllium Against High Temperature Oxidation", Report A66-6, Frankford Arsenal, Philadelphia, Pa. (January, 1966) DMIC No. 66940.

(9) Preliminary information reported by Value Engineering Company, Alexandria, Va., under U. S. Air Force Contract AF 33(615)-5368.

(10) Preliminary information reported by Brown University, Providence, R. I., under U. S. Air Force Contract AF 33(615)-5201.