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Review of Beryllium Technology for Spacecraft Applications

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Abstract

The present status and anticipated future developments in beryllium and beryllium alloys are described. Properties of beryllium together with its advantages and disadvantages are discussed. Current technology and projected progress in fabrication, forming, joining, testing, and applications of beryllium are noted, as are a number of the more important programs in these areas.

Review of Beryllium Technology for Spacecraft Applications

I. Introduction

The purpose of this report is to describe the present status and anticipated future developments in applications of beryllium (Be) and beryllium alloys. The report represents the results of the literature survey portion of a research program being carried out by the Materials Section of the Jet Propulsion Laboratory.

Information reported herein was obtained by surveying pertinent published reports, attendance at meetings and symposia, personal discussions with other workers in these fields, and visits to some of the organizations which are particularly active in the use or development of these materials.

As a result of this extensive survey, it has been possible to draw several conclusions as to the present status, and most likely future progress, in Be and Be alloys. Areas of uncertainty or ambiguity have been identified as well as areas where work remains to be done.

The advantages and disadvantages of Be and Be alloys are discussed, and a brief summary of the present state of the material properties and availability is given. Pitfalls, problems and peculiarities in the testing, forming, joining and usage of Be are noted together with the developmental status of primary and secondary fabrication techniques. Some of the more important current programs are described, and a projection is made of probable advances in the state-of-the-art. A bibliography of reports on Be is presented herein.

Designers have been reluctant to use Be because of its high cost, variability of product, low ductility, and toxicity. Experience with Be as a structural material was also lacking. This situation is beginning to change. In many cases, cost is not a vital factor; in fact, use of Be may lower overall system costs when weight can be saved. Product reproducibility and reliability have improved significantly in recent years. Toxicity has been controlled successfully by careful attention to proper handling procedures such as collecting dust and chips at the tool bit, filtering air and coolant fluids, and careful maintenance of high standards of cleanliness and housekeeping (Refs. 1 and 2).

The present major disadvantage in the use of Be and Be alloys is poor resistance to crack growth. Careful reading of the literature reveals that there is considerable uncertainty and disagreement as to the true sensitivity of Be to cracks, particularly as affected by material properties (Refs. 3–7). Resolution of this uncertainty will provide designers with more accurate data on the fracture sensitivity and allowable flaw size in structural applications, and should increase confidence in Be.

A vital point in the successful application of Be is the need for a cooperative effort between materials, design and structures discipline in order to utilize the material in a way which takes maximum advantage of the material's high modulus, strength, and lightness while minimizing its lack of ductility and its poor resistance to crack propagation. This is the only approach which will permit maximum material utilization and minimum design problems without an extensive iterative process. This interdisciplinary cooperation will permit increased design flexibility and greater materials efficiency at minimum cost.

II. State-of-the-Art

The application of Be to designs which are limited to compression loading is practical at this time without additional development (Refs. 8–10). It is also possible to use Be in simple tension, but biaxial tensile applications require caution in design and material selection. Designs utilizing Be should emphasize applications where resistance to gross buckling, crippling, or flutter is required rather than tensile or biaxial strength (Refs. 8 and 11). The various advantages and disadvantages of Be should be considered carefully during the spacecraft design phase in order to achieve the most effective usage and to prevent problems in fabrication and assembly.

The physical properties of Be, even more than those of most other materials, are affected by the form of the starting material and subsequent processing operations (Refs. 12–15). The best bidirectional properties are obtained from cross-rolled sheet, either from ingot stock or hot-pressed powder compacts. Maximum longitudinal tensile strength is obtained from wire and extrusions; hot-pressed block has lower strength but better bidirectional properties and is less costly. Surface roughness, which may present problems in some applications, is greater in ingot sheet products than in powder sheet.

The major factors which affect physical properties are grain size, grain orientation, and purity, particularly with respect to oxygen (O), silicon (Si), iron (Fe), and aluminum (Al). Highest strength, greatest ductility and greatest resistance to crack propagation occur when grain size is fine (10 μ or less) and equiaxed. Several percent of beryllium oxide (BeO) has been found to improve strength and retard recrystallization and grain growth during hot working. Excessive amounts of Al cause hot shortness during forging or hot working. Reduced Al content gives improved high-temperature strength and ductility (Ref. 16). Iron acts to tie up the Al and improves forgeability. Silicon appears to react with the Al, forming a low-melting grain boundary phase which also causes hot-shortness. Grain boundary segregation of Al, Fe, and Si has been observed, with Fe and Al tending to cosegregate (Ref. 14). The balance between Al, Fe, and Si thus appears to affect fabrication and materials properties (Ref. 17). There are indications that Cu may improve ductility, possibly by blunting the ends of microcracks (Refs. 14, 17). Processing history of the material is also of great importance, largely because of the effect process history has on grain size, orientation, and purity (Refs. 12, 14).

In order to properly characterize Be, it is necessary to know what the starting material was, how it was processed, the final grain size, the chemical composition, and the mechanical properties (Ref. 18). Different combinations of properties are desirable for different applications. The designer and metallurgist should be aware of the process history and properties in order to make the most effective use of all of the attractive properties of Be.

Production of Be mill products is low, and this is a major cause of the high prices, long lead times, and uneven quality. Capital investment in forging, rolling, and surface conditioning equipment cannot be justified by the producers until output and sales increase (Ref. 19). Generally, users have found it easier and cheaper to perform such operations as flattening and final edge milling rather than having the producers do it (Ref. 20).

The importance of uniformity and reliability increases as the design requirements approach the guaranteed minimum strength and elongation values. Most present applications do not utilize a large proportion (i.e., 70% or more) of the tensile strength of Be, so the problem of material uniformity has been avoided. Should a specific application require using almost all of the guaranteed minimum tensile strength available, careful control of incoming materials will be required.

There is little hope that some major breakthrough in ductility improvement will occur (Ref. 13). The brittle behavior appears to be inherent in the material, and neither alloying nor purification seems to hold much promise of significant improvements. The inherent brittleness is caused by a lack of room temperature slip systems. In order to deform plastically, the crystal must have five independent slip systems; Be possesses only four such systems in tension, and none in compression. Therefore, cracks occur when Be is overloaded, acting as a sort of additional slip system and permitting the material to deform (Ref. 13). Knowledgeable personnel at the Air Force Materials Laboratory (AFML) feel that a better understanding of the basic behavior of Be is needed, and that learning how to activate additional slip systems at room temperature is one field which needs more effort (Refs. 9, 21). It is recognized that it may prove impossible to activate such additional slip systems at normal temperatures.

It has been reported that the presence of microcracks sometimes reduces the brittle failure tendency of Be, possibly by allowing deformation without catastrophic failure or by retarding growth of larger cracks (Refs. 6, 22). This phenomenon warrants further study. It may be possible to develop a material which is less sensitive to surface defects, notches, edge cracks, etc., or at least to determine accurately the true sensitivity of Be mechanical properties to the presence of cracks or notches.

The fatigue strength of Be is excellent, exeeding that of Al or Ti for 10^5 cycles or more (Refs. 4, 5, 23).

A. Fabrication

Most Be mill products are available as 36- × 96-in. sheets which have been formed from hot-pressed −200-mesh powder, jacketed in steel and hot cross-rolled. After rolling, the steel jacket is removed and the beryllium surface is ground and then etched to remove grinding marks, cracks, and twins. Another form is hot-pressed block, which is also formed from powder, but is either not reduced by further working, or is reduced very slightly to increase density or obtain a desired size or shape. A newer product is ingot sheet, which is formed by vacuum induction casting followed by forging, upset forging, extruding, and cross-rolling either separately or in combination. Preliminary working operations aid in breaking up the as-cast structure and refining the grain size; normally only one of the primary forming operations is used before rolling. Ingot sheet typically is of higher purity, but has somewhat poorer surface finish and mechanical properties than powder sheet. The lower properties are believed to be caused by the relatively coarse grain size. Ingots prepared from −325-mesh powder have given improved yield and tensile strengths owing to the finer final grain size (Ref. 14).

Each of these mill products possesses certain advantages and disadvantages. Use of one or another of them will be dictated by design, application, and cost factors.

Final fabrication into components may be done by machining, hot-forming, forging, or extrusion (if the shape is relatively simple) or combinations of these. Machining can be done with normal shop tools and procedures providing that due care is exercised in the control and containment of the toxic dusts. For example, rough sawing is done with a fine-toothed blade in a band saw at 500 ft/min. Shaping and milling are performed with standard carbide tools. Tool wear is about 5 times as great as for Al. Drilling is generally done using a special drill[1] which senses drilling pressures and maintains constant torque. Backup plates are recommended for sawing or drilling thin, unsupported stock to avoid applying bending moments to the Be which might cause cracking or delamination.

After final machining, at least 2 mils is removed from the surface by etching to remove twins and microcracks (Refs. 12, 24–27). Selection of an etching solution seems to be a matter of balancing off final surface finish, metal removal rate, and ease of solution control. Etchant composition and temperature usually are the most critical factors. Typical etchants are given in Refs. 26 and 28. In general, users of Be agree that fabrication is not difficult or unreasonably expensive, providing that proper care is taken during machining and handling to prevent surface scratches, cracks or other handling damage (Refs. 29, 30).

Fairly complex sheet metal components may be made by hot-forming at about 1350°F (Refs. 30, 31). Beryllium may be hot-worked successfully because additional prism slip becomes possible above 940°F. Below this temperature the critical resolved shear stress for basal slip is lower, and the prism slip cannot occur (Ref. 13). To form Be, the stock, usually sheet, is placed into a heated die and the part is formed as pressure slowly is applied to the die (Refs. 5, 12, 31, 32). Normally, forming is done in ceramic dies, but some workers have had limited success forming smaller parts in stainless steel or Inconel dies (Refs. 29–35). Relatively simple shapes such as angles, channels, and spacers have been formed in this

[1]Tornetic controlled torque drill, manufactured by Dyna Systems, Inc., Torrance, Calif.

way (Refs. 23, 36–38). Channel sections almost 8 ft long have been produced using specially designed stainless steel punches and dies. A few more complex parts such as domes, double convex sheets, and cylindrical sections also have been made successfully (Refs. 39–41). Bends with a 5T–6T radius (T = thickness) are possible with powder sheet, and 3T–4T can be obtained with ingot sheet. The quoted results are for parts formed at 1300–1350°F. Bending processes usually result in a higher scrap loss than machining, but in neither type of operation are losses considered to be a serious problem by those who have been performing the work.

Both open and closed die forgings have been formed successfully. Usually it is necessary to jacket the Be billet with steel or stainless steel before forging; if this precaution is taken, relatively complex parts may be forged successfully (Refs. 42–44). More recently, aircraft components, such as brackets, have been forged bare, both in open and closed dies. An important limitation of this process is the quality and forgeability of the input stock (Ref. 45).

Extrusion of Be has been demonstrated for a number of different shapes (Refs. 46–48). Although common shapes, such as tubes can be formed, they are not readily available; long lead times may be required for delivery, even for relatively standard sizes. The major problems encountered during extrusion are the need for higher ram pressures (relative to aluminum), die design at the inlet, and the tendency for the Be to seize and gall. Galling can be eliminated by jacketing the Be billet in stainless steel, but this increases material costs and requires expensive operations in both the cladding of the Be and removal of the cladding after extrusion. Various die lubricants have been tried, but without complete success. The approaches used for forming Be wire seem to have provided the best answers to the lubrication problem. One organization sheaths the Be in Ni before drawing, and etches away the Ni surface after drawing (Ref. 49). Another dips the Be into a graphite type of lubricant before extruding and drawing (Ref. 50). Both methods can result in embedding the lubricant in the surface of the Be, reducing mechanical properties appreciably.

B. Joining

Presently used joining techniques are rather limited; mechanical fastening and adhesive bonding are most often used, while welding, braze welding, and brazing and diffusion bonding are employed where loss of strength due to recrystallization and grain growth either can be retarded by proper joint and fixture design or is not important for the particular application involved.

Mechanical fastening is well developed and has proven very successful. The major problems are preventing joint rotation and avoiding cracking or delaminating the sheets while drilling the holes and installing rivets. If threaded holes are tapped and drilled, the threads must be etched before use to remove surface damage. Investigations also have been made of joint design, the effect of using different types of fasteners, and the usefulness of compound joints, i.e., mechanical fastener plus adhesive (Ref. 51).

If a lower level of shear strength is acceptable, adhesive bonding can be used successfully. A number of sizable structures have been adhesively joined with satisfactory results (Refs. 12, 35, 51–55). In fact, it is planned to adhesively bond all of the structural components of a solar panel array having individual panel sections as large as 13 × 8.5 ft (Ref. 52). When application of pressure and heat during bonding is impractical, either because of joint design or the effects on adjacent materials, adhesive bonding is less effective. Room temperature curing adhesives normally have lower shear and peel strengths, and are less desirable where high strength is required.

Both spot welding and electron beam welding are being investigated as joining techniques, but neither appears to hold much promise because of the high thermal conductivity of Be and the extensive grain growth which results in brittle joints (Ref. 56). Battelle has reported recently that they have successfully joined Be sheets ranging from 0.020 to 0.250 in. thick by electron beam welding. High oxide content seems to inhibit good wetting and joining (Ref. 57), while sheets of low oxide content are more prone to weld cracking. Addition of preplaced Al shims aids welding of 0.25-in. sheets as does the addition of filler wire (Ref. 58).

The most common braze alloys at present are Ag-base and AlSi, although some Zn alloys are also used (Refs. 5, 12, 51). Development of improved and lower-temperature braze alloys is being conducted to improve wetting and bonding, increase joint strength and remelt temperatures, widen process tolerances, and lower brazing temperatures to 1200–1400°F. Brazing at this temperature avoids the 1500–1600°F recrystallization range. Indications are that most of these objectives can be met within the next few years; brazing in argon rather than vacuum, use of beryl formers in the braze alloy, and control of the oxide content of the Be all will aid in obtaining better and more reliable braze joints (Ref. 59).

Diffusion bonding of Be is in an early stage of development. So far results have been spotty, both with and without bonding aids (Refs. 51, 60, 61). The process seems to be adversely affected by a number of variables, not all of which have been identified; they are thought to include oxide content, surface preparation, time, temperature, pressure, atmosphere, and nature of bonding aids, if any.

C. Beryllium Alloys

The only successful family of Be alloys developed to date are the Be-Al series, commonly known as Lockalloys. Aluminum contents of from 24 to 43% have been prepared and tested, but the standard commercial grade is the 38% Al alloy. Actually this is a dispersion of Al in Be rather than a true alloy. The advantages are greater ductility, lower cost, and elimination of the requirement for etching after machining. Lockalloy can be cold-formed and punched in the annealed condition. It may be spot-, seam-, and projection-welded successfully, and is generally easier to join and fabricate than commercially pure beryllium. The penalty is a reduction in modulus to about that of steel, and appreciably lower strength, with a density about 25% less than that of Al (Refs. 17, 62–69). Reproducibility of physical properties from heat to heat appears to be satisfactory (Ref. 62). Not much Lockalloy is being used at present, and it is not as widely available as commercially pure Be. There is a lack of experience in the design and use of Lockalloy components which seems to inhibit many designers from using it.

Attempts to develop other alloys by adding elements such as Fe have resulted in further embrittling the Be (Refs. 17, 70). However, additions of Cu to Be in an attempt to prepare usable solid solution alloys are promising. Ingots have been extruded which extrude much like unalloyed Be. More studies of these alloys are continuing (Ref. 71).

D. Present Materials Availability

Beryllium suppliers have stated they can fill orders for 10 to 12 3- × 8-ft hot cross-rolled sheets within 8 weeks. Similar quantities of Be ingot sheet and hot pressed block are said to be available in slightly longer times. However, some users have had difficulty obtaining material on these delivery schedules (Ref. 16). Recently, sheets as long as 180 in. were rolled successfully from powder-derived material.

Several users have complained about the quality of the sheet as received from the mill. Most common complaints are lack of sheet flatness and the presence of edge cracks; these problems reportedly are not serious in more recent production (Refs. 20, 36). Inability to meet specifications on physical properties is occasionally mentioned, but apparently 100% mill testing has kept low yield and tensile properties from becoming a serious problem. Since many applications require relatively low strengths, almost all of the production can be sold without major difficulty (Ref. 16).

Small quantities of 0.001–0.005 in. foil have been produced, but it is very expensive and the uniformity and reproducibility of this form of Be is not established. The minimum standard thickness obtainable is 0.020 in. However, some 0.010 in. material is available in small sizes. Rolling below 0.020 in. often results in excessive grain orientation; bidirectional properties are reduced; poor surface finish results; thickness varies; and lack of flatness becomes troublesome. Thin gauges are usually formed by etching heavier gauge stock (Ref. 30), which is expensive.

E. Anticipated Future Progress

Both Berylco[2] and Brush Beryllium[3] are working to improve material quality and reliability. A major requirement is more and better in-house processing capability, longer mill runs, and better process controls (Refs. 19, 70). The need for these changes is recognized, and they will be made eventually; exactly how soon will depend to a large degree on the future usage of Be products.

A definite improvement in material quality and uniformity already has occurred and has been acknowledged by several Be users (Refs. 24, 29). Further improvements are certain, but the exact timing is not. In addition to improved hot-pressed and rolled sheet, increasing quantities of ingot sheet are becoming available. It is likely that alloying will improve the mechanical properties,

[2]The Beryllium Corp., Reading, Pa.

[3]The Brush Beryllium Co., Cleveland, Ohio.

and better rolling equipment will permit reductions to thinner gauges without excessive loss of properties. Thinner sheet in larger sizes also should become available as a standard item within the next several years. Production quantities of foils are not envisioned in the near future, but are a strong possibility within several years – or sooner if a definite requirement for significant amounts can be demonstrated.

It will be some time, perhaps as much as 3 to 5 years, before Be sheet can be ordered from the mill in the same way that Ti or some of the refractory metals are at this time. Just when it will become a standard material will depend largely upon the success of designers and engineers in applying it and the size of the market.

The first major improvements in fabrication and assembly will be related directly to material quality and uniformity. Selection of individual sheets for physical and mechanical properties will become less of a necessity. Additional straightening and flattening operations will not be required for most applications. Machining and handling will become standard operations, routinely performed by even more organizations than at present. This will occur partly through normal movement of personnel (and techniques) throughout industry and partly through increased demand for these services, which will make it more attractive and profitable for additional companies to develop Be capabilities.

Assembly will be easier as more people become experienced with the techniques, as fit-up problems are reduced by better flatness of as-received stock, and as more assembly techniques become available. These new methods will encompass Be fasteners (both blind and threaded), improved rivets and riveting procedures, a wider range of braze alloys, and diffusion bonding, electron beam welding, or braze welding. More attention to design will permit better joint configurations and reduce the complexity of assembly. In some instances, combinations of Be, Be-Al, and Al may be used to improve fabrication and assembly of particularly difficult shapes or joints.

III. Recent Programs

Many organizations are conducting Be development programs. Some are sponsored by industrial organizations, some by the AEC, some by other NASA installations; many are Air Force supported.[4] A brief summary of a number of the more pertinent programs is given below.

A. Applications

McDonnell Aircraft has fabricated and successfully tested wing boxes and a rudder section made of a Be skin and stiffeners, joined with bolts and mechanical blind rivets. Failure occurred at 150–160% of design stress, and no primary failures through fastener holes were observed (Refs. 72–73). The material used had a design yield strength of 50,000 psi and design ultimate of 70,000 psi (Ref. 74). Republic Aviation made a box beam section from sheet for Marshall Space Flight Center; fastening was by mechanical blind rivets. They reported little difficulty in working with the material (Ref. 36). This section is now being tested. Another box beam fabricated for MSFC has been assembled using Be fasteners which are being made by Standard Pressed Steel.[5] The beam should be tested shortly.

Boeing recently completed a program for the Air Force on the fabrication and testing of a solar panel spar 76 in. long, formed from sheet. It failed at about 2½ times design load. Failure was initiated at a defect about 0.040 in. in diameter (Ref. 37). Boeing is in the early stages of another solar panel development program for JPL, the ultimate object of which is to fabricate and test a 20 W/lb array with over 1200 sq ft of surface area. In order to satisfy this requirement, a Be structure is required. Beryllium spars up to 13 ft long must be fabricated, formed, and adhesively joined to other members (Refs. 52, 74). Lockheed is fabricating a number of *Agena* components from Be as a production operation without any significant difficulties. Machining, forming, and etching are performed routinely with little scrap loss (Refs. 29, 38). Most applications seem to be in noncritical or lightly loaded areas.

At Langley Research Center, NASA is fabricating a Be truss structure based upon the *Mariner II* design. Extruded Be, Al, and Lockalloy tubing 0.25 to 0.75 in. in diameter with 0.020–0.040 in. walls is being used in the structural members. Major problems are joint design and

[4]The Air Force has been and is continuing to be the major sponsor of programs ranging from basic studies of single and polycrystalline Be fabrication of components for structural test such as wing boxes, rudder sections and solar panel spars.

[5]Standard Pressed Steel, Philadelphia, Pa.

adequate stress transfer from strut to strut at the joints. Use of aluminum joints imposes a heavy weight penalty, while Be "spider" joints are costly and difficult to fabricate and assemble. Present design is a compromise in which the "spider" is Al, with short Al tubes adhesively bonded to the Be with a slip collar (Ref. 75).

Solar[6] is producing a similar truss structure to be used as a gimbal support for *Saturn* guidance engines. Extruded Be tubing 11 ft long, having a 5-in. diameter with a 0.125-in. wall will be connected at the ends by forged and machined Be caps. Joining will be by adhesives. Only 3-ft lengths have been extruded so far, but no trouble is anticipated with longer lengths. Surface finish, uniformity, and tensile strength are considered to be very good (Ref. 60).

North American is using hot-pressed block for instruments, containers, and other noncritical and nonstructural applications. They have had some problems with cracks in the as-received materials but claim no problems in machining and brazing parts (Refs. 76, 77). The shroud nose dome which encloses *Lunar Orbiter* during launch was fabricated by Boeing by machining from hot pressed block (Ref. 78). Rocketdyne is developing and fabricating Be rocket nozzles for use in small rocket motors. Some test data is available (Ref. 79).

B. Joining

Several programs are underway to develop diffusion bonding techniques for Be. Solar, Lockheed, and North American had tried to spot diffusion bond Be sheets with rather erratic results (Refs. 51, 60, 61). Lockheed has diffusion-bonded sheets successfully by adding Al or Cu to the interface (Ref. 80). Boeing also reports having some success diffusion-bonding Be on a small scale (Ref. 81). Cleaning procedures and the time lag between cleaning and bonding seem to be very important. The variation in oxide content of the sheet also affects bond quality and reproducibility (Refs. 19, 82). Battelle[7] has gas-pressure-bonded Be successfully, but the process is expensive and not fully developed; it is not applicable to some shapes and joint configurations which would be of interest for spacecraft applications, although some very complex shapes have been formed at relatively high tooling costs (Refs. 83–85).

Solar is conducting a study of braze alloys and brazing techniques (Ref. 59). Low oxide content is essential for optimum braze flow and joint strength. Several Ag-base alloys have been developed which appear to wet and flow well and have good lap shear strength. The best of these are being selected for additional development under a follow-on Air Force program. Several promising Ti-base alloys also are under development. Earlier work by Aeronca[8] and Lockheed (Refs. 40, 41, 51, 56) resulted in braze alloys and techniques which gave good results but had limitations, particularly because of high brazing temperature, low remelt temperature, low joint strength, and uncertain reproducibility. Other organizations conducting Be brazing programs include Bi-Braze Corporation,[9] Union Carbide,[10] and MIT.

Battelle has electron-beam-welded Be sheets successfully. Although good welds have been obtained with little porosity or undercutting and essentially no microcracks, joint efficiencies have been low. Best results were obtained with 0.020- and 0.062-in. sheets; welds in 0.250-in. sheet were much more difficult to prepare without undercutting, cracks, or porosity.

The oxide content must be less than 0.7% for best results; this finding agrees with the brazing and diffusion bonding studies cited above (Ref. 57). Autonetics[11] and Lawrence Radiation Laboratory[12] also have joined Be by electron beam welding (Ref. 56). Lawrence Radiation Laboratory employed a prebuttering technique (precoating the joint with braze or weld metal) in the joint areas. In studying electron beam welding of Lockalloy, LRL found that although there was incomplete penetration, welds in 0.010-in. sheet were stronger than the base metal.

Several organizations have welded Be successfully by tungsten inert gas (TIG) welding both with and without prebuttered joints (Refs. 41, 56, 86, 87). LRL listed welding parameters in Ref. 56. Berylco is studying both butt and projection welding.

Adhesive bonding is well developed as a Be joining technique (Refs. 23, 41, 55, 88); little new work is being

[6]Division of International Harvester Co., San Diego, Calif.

[7]Battelle Memorial Institute, Columbus, Ohio.

[8]Aeronca Manufacturing Corp., Middletown, Ohio.

[9]Bi-Braze Corp., Glen Cove, New York.

[10]Union Carbide Y-12 Plant, Oak Ridge, Tenn.

[11]Autonetics Division of North American Aviation, Inc., Anaheim, Calif.

[12]Lawrence Radiation Laboratory, Livermore, Calif.

conducted except that Boeing is examining several 3M Company[13] structural adhesives for use in the large area solar panel program (Ref. 89).

C. Fabrication

Forging development is being done primarily by Ladish,[14] Brush, and TRW.[15] Successful cylinders up to 13 in. high by 31 in. in diameter have been formed by ring rolling; cylinders up to 16 in. high by 13 in. in diameter have been forged bare. Other shapes such as discs, rectangular beams, hemispheres and hollow shafts also have been forged (Refs. 12, 17, 42–46, 89). Autonetics Division of North American has studied the effects of forging variables on directionality of properties (Ref. 43).

Nuclear Metals[16] and Berylco have done extensive development of Be extrusion, succeeding in extruding shapes up to 41 ft long. Sections have included tubing, rods, finned tubes, rectangles, I's H's, hat sections, and squares. Uniformity of properties from end to end along the extrusion is reported to be good, but transverse mechanical strengths were low (Refs. 12, 17, 46–48).

Formability studies are being conducted by Hughes, Lockheed, and Boeing. The effects of bend radius, forming temperature, and material source (powder or ingot) were studied. Ingot sheet may be formed successfully at lower temperatures than powder sheet, or, if formed at the same temperature, ingot sheet can be formed more severely without cracking (Refs. 5, 30, 39, 40, 53).

D. Properties of Beryllium

The Air Force is sponsoring studies of the properties and behavior of polycrystalline beryllium to better understand the ductility problem and attempt to find a solution (or establish with certainty that no solution exists). Some of the work is being done at Wright-Patterson AFB, and some is being done at Nuclear Metals and Franklin Institute[17] (Refs. 9, 90).

The fracture behavior, crack growth, and sensitivity to notches and cracks of Be recently came under study by several organizations. Previous data in this field is scattered, incomplete, and contradictory. In an attempt to resolve this uncertainty, various aspects of the fracture behavior of Be with induced sharp-edged defects are being examined by Westinghouse,[18] Battelle, Sandia,[19] Boeing, and the Flight Dynamics Laboratory of the Air Force at Wright Field (Refs. 6, 21, 22, 33, 52, 91, 92). Notch sensitivity of Be has been studied briefly by Lockheed, Boeing, Douglas, and Brush Beryllium at room temperature, cryogenic temperatures, and elevated temperatures (Refs. 3, 5, 33, 52, 93, 94). Battelle has compiled the information available in 1958 in an extensive bibliography (Ref. 95). The data at elevated temperatures indicated that for a stress concentration factor (K_t) of 4 there is actually some strengthening of the Be; at room temperature or below there is some lowering of the Be strength, but it is not severe. This is true both for powder and ingot sheet. For $K_t = 2.5$, at $-320°$F, notched strength of ingot sheet actually exceeded unnotched strengths (Ref. 3). Preliminary data reported by Westinghouse indicated that crack growth may stop when the crack enters a low stress region (Ref. 22).

The Air Force Flight Dynamics Laboratory recently awarded a contract to develop techniques to minimize crack propagation in Be aircraft structures by improved design and fabrication techniques. A JPL program to determine the effects of material and composition variations on notch strength was begun recently, and should further help to clarify the fracture behavior of Be.

E. Beryllium Alloys

Both Hughes and Lockheed are enthusiastic about the potential of Lockalloy (Refs. 29, 30, 53). A range of Al contents of from 24 to 43% has been studied; the 38% Al alloy is presently most widely used (Refs. 53, 65–69). The major advantages are ease of fabrication, handling, and assembly. Lockalloy in the annealed condition is easily formed (it can be bent cold to a 6T to 8T radius), drilled, and machined; it also can be joined successfully by welding (both spot and seam) and brazing. This permits more complex and extensive forming and machining operations, without the need for a final etch to remove surface microcracks or twins. The physical and mechanical properties of Lockalloy are tabulated and compared with Be, Al, and Mg in Table 1 (Refs. 17, 49, 50, 53, 96, 97).

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[13]Minnesota Mining and Manufacturing Company, Rochester, Minn.

[14]Ladish Co., Cudahy, Wis.

[15]TRW, Cleveland, Ohio.

[16]Nuclear Metals Division of Textron, Concord, Mass.

[17]The Franklin Institute, Philadelphia, Pa.

[18]Westinghouse Electric Corp., Astronuclear Division, Large, Pa.

[19]Sandia Corp., Albuquerque, N.M.

Table 1. Comparative properties of Be and alloys of Ti, Al, and Mg (all properties at room temperature)

	Cross rolled Be sheet[a]	Cross rolled Be sheet[b]	Hot pressed Be block[c]	62 Be-38 Al sheet	Mg alloy HM21A-T8	Al alloy 7075T6	Ti alloy sheet Ti-6V-4 Al
Tensile yield strength, psi	75,000	53,800	48,400	50,400	37,000	72,200	147,000
Tensile ultimate strength, psi	55,400	40,300	40,700	36,600	30,000	63,200	137,000
Tensile modulus $\times 10^6$, psi	43.1		42.4	29.2	6.50	10.3	16.0
Tensile elongation, %	8	3.2	1	8.1	4	7	10
Compressive yield strength, psi	58.3		27,000	34,200	22,000	68,000	126,000
Compressive modulus $\times 10^6$, psi	42.6		42.6	29.1	6.5	10.0	16.4
Density, lb/in.^{3}	0.066	0.066	0.066	0.0756	0.064	0.101	0.160
Coefficient of thermal expansion, in./in./°F (77-212°F)	6.4×10^6			9.0×10^6	21.8	12.9	4.8
Thermal conductivity, Btu/(hr ft^2°F/ft)	104		104	123	80 (est)	76	3.8

[a]Powder-derived; all values in longitudinal direction.

[b]Ingot-derived; all values in longitudinal direction.

[c]SR-200 powder.

Hughes is sponsoring development of Be and Be-Al alloy components to replace Al and Mg in satellite applications. Analytical studies indicate that considerable weight savings are possible. Some of these weight savings are obtained by use of thin sheet material, which is not normally supplied by the producers; it is chemically milled to 0.005 or 0.010 in. from 0.020- or 0.025-in. sheet (Refs. 30, 53), which imposes a severe cost penalty. However, if a large market for this sheet develops, both Hughes and Brush Beryllium are confident that thin gauges can be produced successfully in quantity (Refs. 16, 30).

A substantial order recently was placed for Lockalloy to be used on *Minuteman*. This may be the beginning of an appreciable use of Be alloys. Berylco is in the early stages of a program to develop Be-Cu alloys by casting and extrusion. So far the progress is encouraging (Ref. 71).

The above programs do not include all of the current beryllium effort. However, they are the more important and extensive programs, and include those most directly applicable to spacecraft requirements. A list of current government-sponsored Be programs is contained in Ref. 98.

IV. Conclusions

Beryllium possesses significant advantages in strength-to-weight ratio and modulus-to-weight ratio as compared with presently used spacecraft structural materials.

Beryllium is presently usable for compression-limited applications without further development. It can be used in simple tension successfully; but in biaxial tension care must be exercised in design, fabrication, and assembly.

Joining of beryllium with mechanical fasteners, solder, braze welding, and adhesives is well developed, and can be considered acceptable for spacecraft use without further development. Joining by brazing, welding, diffusion bonding and electron beam welding has been demonstrated successfully, and can be considered to be in the advanced development stage. All of these latter joining methods require at least some refinement.

Forming and machining beryllium is essentially fully developed.

Problems still exist in the areas of material quality and uniformity, but improvements are being made. Further improvements are expected in the future.

The fracture behavior and effect of sharp-edged defects on different types of beryllium material are not well known or understood. Present data is incomplete and conflicting. Programs presently underway should clarify this problem.

Procedures have been developed for containing the toxic beryllium dusts formed during machining. If proper care is observed, the hazards involved in handling and fabricating beryllium can be minimized so that toxicity is not a problem.

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