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A SURVEY OF BERYLLIUM TECHNOLOGY
AND NUCLEAR APPLICATIONS

Hui Pih

OAK RIDGE NATIONAL LABORATORY

operated by

UNION CARBIDE CORPORATION

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General Engineering Division

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JUNE 1969

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee
operated by
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A SURVEY OF BERYLLIUM TECHNOLOGY AND NUCLEAR APPLICATIONS

Abstract

Information related to the material properties of beryllium and to the structural and nuclear applications of beryllium is widely scattered in the technical literature. A literature survey was conducted, and the resulting compilation of information presented in this report is directed toward certain areas of the use of beryllium in nuclear applications that may be of particular interest to the designer of nuclear reactors. These areas include the effects of neutron irradiation on beryllium, the design considerations in the use of beryllium, and beryllium fabrication methods.

1. INTRODUCTION

Beryllium has many desirable nuclear properties, such as an extremely low neutron-absorption cross section, a high neutron-scattering cross section, and a low atomic weight, that make it a most attractive material for reflectors, moderators, and fuel canning and cladding in nuclear reactors. Its high modulus of elasticity, low density, high melting point, high specific heat, and low thermal expansion also make beryllium a potentially good structural material for aerospace applications. However, its relatively high cost, lack of ductility, swelling and further loss of ductility caused by neutron irradiation, poor resistance or corrosion by H_2O and CO_2 , and its toxicity impose many limitations on the application of beryllium.

A literature survey was conducted to obtain information on some of the important properties of beryllium, and the results of that survey are reported here. It is recognized that during the 10-year span between 1955 and 1965, at least three books on beryllium^{1,2,3} were published and several conferences on beryllium were held and the proceedings^{4,5,6,7} released. But large amounts of technical information are scattered in the reports of government agencies such as the Atomic Energy Commission,

the Air Force, and the National Aeronautics and Space Administration. Obviously, the results of the literature survey presented in this report cannot deal comprehensively with the whole problem of beryllium. The information presented here is therefore limited to certain areas of particular interest related to the use of beryllium in nuclear applications. These areas include the effects of neutron irradiation on beryllium, design considerations in the use of beryllium as a structural material and as a nuclear reactor material, and beryllium fabrication methods.

2. APPLICATIONS OF BERYLLIUM

Beryllium has been used in nuclear and aerospace applications, and these are the primary interests of this survey. However, beryllium has also been used as an important alloying element, such as in beryllium bronze; as a neutron source based on the (α ,n) reaction; as a photoneutron source (γ ,n); and as an X-ray tube window because of its high X-ray transmission capabilities.^{1,2}

Nuclear Applications

The main application of beryllium has been in the nuclear field, and it has been used or considered for use as a reflector material, a moderator, a cladding material for fuel elements, and as a fuel diluent in different nuclear reactors.^{8,9}

Reflectors

Beryllium has a rather high neutron-scattering cross section and the lowest neutron-absorption cross section of all the metals because of its low atomic weight and high atomic density. These factors make beryllium an excellent material for reflectors for most high-flux research and test reactors throughout the world. Beryllium reflectors are used in various testing reactors such as the Materials Testing Reactor (MTR), Engineering Test Reactor (ETR), Experimental Breeder Reactor No. 2 (EBR-2), and the Advanced Engineering Test Reactor (AETR). Beryllium is also used as the reflector material in many of the high-flux research reactors such as the Oak Ridge Research Reactor (ORR) and the High Flux Isotope Reactor (HFIR) in the United States of America, Pegasus and Osiris in France, the Japanese Material Testing Reactor (JMTR) in Japan, and the WWR-M and R-M Research Reactors in the Union of Soviet Socialist Republics.

One of the more interesting developments has been the use of beryllium reflectors in direct conversion reactors to transform thermal energy into

electrical energy for space applications, Systems for Nuclear Auxiliary Power (SNAP). Some of these systems, such as SNAP-2/10A and SNAP-8, have electric power output goals of up to 30 kw and involve the use of beryllium reflectors operating at temperatures up to 1400°F. A similar application, "Remaska", has been devised in the USSR.

Moderators

Reactors that have an average fission energy in the intermediate or thermal range of neutron energy must have a means (the moderator) incorporated within them for slowing down the fast neutron. The basic requirements for good moderator materials include

1. the capability for rapidly reducing neutron energy,
2. a high neutron-scattering cross section and a large average neutron energy loss per collision (mass of the atom is nearly that of the neutron),
3. a low neutron-absorption cross section for thermal neutrons,
4. good heat transfer characteristics,
5. dimensional stability under heat and neutron irradiation, and
6. if the material is a solid, it must have adequate strength at the operating temperature under irradiation and external loading conditions.

Only four elements of low atomic weight fulfill the requirements for low neutron-absorption cross section and high neutron-scattering cross section. These elements are hydrogen, deuterium, beryllium, and graphite; and the basic nuclear data¹⁰ for these elements are given in Table 1.

Table 1. Basic Nuclear Characteristics of Some Moderator Materials¹⁰

Element	Atomic Weight	Number of Atoms per $\text{cm}^3 \times 10^{-24}$	Density (g/cm^3)	Scattering Cross Section (barns/atom)	Absorption Cross Section (barns/atom)	Slowing Down Power
Hydrogen	1.008	0.0054	0.0090	20.3	0.33	0.11
Deuterium	2.02	0.0054	0.0180	3.3	0.00046	0.013
Beryllium	9.01	0.124	1.85	6.1	0.009	0.16
Carbon	12.01	0.080	1.60	4.7	0.0045	0.060

Of these four elements, hydrogen and deuterium present fire hazards in their elemental forms but can be used as moderators in the form of light and heavy water, whereas beryllium and carbon can be used in any form as long as the purity level is high enough. Beryllium can be used in metal form or in carbide, oxide, and fluoride forms. Carbon is used in the form of graphite. Because of its good physical and mechanical properties, ease of machining, and its relatively low cost, graphite was the first solid moderating material used in a nuclear reactor and it is still used in many reactors. When beryllium is used as the moderator material, it must be of extremely high purity (reactor grade) because small amounts of impurities increase the thermal neutron absorption cross section considerably. However, beryllium has not been used as the moderator in any large reactor because of its high costs, but high-purity beryllium oxide is being used for the moderator and reflector material. The density of beryllium oxide is about 65% higher than that of beryllium metal, while the price is about 20 to 25% of that of the metal. The dimensional changes of the oxide form under irradiation are also less than those of the metal form.

Fuel Cladding

Beryllium has been considered as a possible material for fuel cladding in gas-cooled power reactors operated at high temperatures. For this application, the cladding material would be in the location of maximum fast neutron flux, and it was found that the neutron irradiation in combination with high temperature caused swelling of beryllium and a reduction of its already low ductility. Beryllium also has poor corrosion resistance to H_2O and CO_2 . With these limitations, the interest in the use of beryllium as a cladding material is almost lost.

Fuel Diluent

When used as a fuel diluent material, beryllium will be in the region of maximum neutron flux. Hence, irradiation swelling is to be expected if the temperature is sufficiently high.

Aerospace Applications

Although nuclear applications of beryllium are quite prevalent in both development testing and in production, the major interest in beryllium applications has currently shifted to the aerospace industry.^{3,8,11,12} With the understanding that the main interest of this report is in the nuclear applications of beryllium, the aerospace applications are discussed briefly. In order to bring out the advantages of beryllium over other metals, the important physical properties of beryllium are compared with those of several commonly used structural materials in Table 2. With this table providing the background information, the aerospace applications of beryllium in structures and heat sinks are discussed.

Table 2. Physical Properties of Beryllium Compared With Those of Other Structural Materials^{1,2}

Property	Material				
	Be	Al	Mg	Ti	Fe
Density, lb/in. ³	0.066	0.10	0.065	0.165	0.280
Thermal conductivity C.G.S. units at 0°C	0.45	0.5	0.4	0.04	0.2
Specific heat C.G.S. units at 0°C	0.4	0.2	0.25	0.13	0.11
Coefficient of expansion 10 ⁻⁶ (°C) ⁻¹ , 20-100°C	11.5	23	26	8.5	11.7
Melting point, °C	1283	660	650	1660	1540
Neutron absorption cross section, barns per atom	0.009	0.230	0.065	5.6	2.5

Structures

Beryllium has a very low density, a rather high modulus of elasticity, a high damping capacity, and its coefficient of thermal expansion is very close to that of steel. Except for its low ductility, beryllium offers definite structural advantages in aerospace applications. It has been used for leading edges, secondary wing skins, some fuselage plating, and control surfaces in airplanes. It has been used in the interconnect structures of upper stages, the internal structures of the final stages,

and in the nose shells of missiles and spacecrafts. Beryllium has also been used for items in guidance and control systems such as rotating gimbals, gimbal rings, trunnions, supports, compartments, and computer hardware and housings.

Heat Sinks

Beryllium metal also has a relatively high thermal conductivity, high specific heat, and a relatively high melting point. It has been used as a heat sink in airplanes, missiles, and spacecrafts. This application in airplanes includes fuselage noses, inlet ducts, brakes, and multiwall enclosure structures for the crew. In space applications, it has been used in multiwall enclosure structures for various payloads and in heat shields for various parachute-type recoveries. Beryllium has the potential for application in torsional restraint structures for tank clusters, multiwall structures for space platforms, re-entry structures, internal structures in insulated and cooled structures, and in internal cabin structures for re-entry vehicles and certain parachute recovery capsules.

3. THE EFFECTS OF NEUTRON IRRADIATION ON BERYLLIUM

Investigations of the effects of neutron irradiation on beryllium have been conducted since the late fifties, and reports have been made on the swelling of beryllium reflector parts in the MTR¹³ and in the ORR¹⁴ after certain lengths of operation. However, there has continued to be an interest in the irradiation effect on beryllium although in a somewhat reduced scale in recent years. Currently, beryllium is being used as a reflector material in the HFIR.

Besides the normal effect caused by the displacement of atoms, nuclear reactions caused by neutron irradiation also occur in beryllium. These reactions are from fast neutron (> 1 Mev) through (n,2n) capture reactions,

and through (n, α) capture reactions,

From thermal neutrons the reactions are

and

Most of the gases produced in these reactions are helium -4, some tritium helium -3, and hydrogen -1. The influence of these gases on the physical and mechanical properties of beryllium depends upon the temperature and the fluence (neutron flux integrated with respect to time). The effects of neutron irradiation on the volume (swelling), mechanical properties, and thermal conductivity of beryllium are discussed in this chapter.

Swelling

According to the information reported by Ellis and Perryman,¹⁵ about 2.2 to 2.6 cm³ of gas is produced from 1 cm³ of beryllium subjected to a fast fluence of 10^{21} n/cm². However, Ellis and Perryman did not detect much increase in the density of the MTR beryllium irradiated to 10^{22} n/cm² below a temperature of 440°C. Tests were conducted by Rich, Redding, and Barnes¹⁶ on a beryllium shim rod from the MTR that was irradiated by fast neutrons to a fluence of about 7.6×10^{21} n/cm² at a temperature of about 70°C. They did not find any sizable swelling when annealed below 500°C.

Further tests were made by Rich, Walters, and Barnes¹⁷ on hot-pressed beryllium produced by the Brush Beryllium Company from 200-mesh powder. Irradiation by fast neutrons to a fluence of about 2.75×10^{21} n/cm² at temperatures between 280 and 480°C produced little swelling but marked change in mechanical properties. Heating for one hour at temperatures below 800°C did not produce any swelling, and after being held at a temperature of 600°C for four weeks, there was less than 0.5% decrease in the density of the beryllium. From studies with the electron microscope made by these researchers and also from further observations made by Barnes,¹⁸ it was found that the helium atoms remain in solid solution in the matrix at low temperatures or as very small bubbles that do not affect the total volume. At higher temperatures, the helium atoms agglomerated into larger bubbles through the diffusion process and caused a considerable increase in the volume of the beryllium.

No significant change in the volume of beryllium irradiated at temperatures up to 680°C and to fast fluences of 1.5×10^{20} n/cm² was found by Hickman.¹⁹ Hot-pressed and extruded specimens of Pechiney Company and Brush Company beryllium were examined by Walters²⁰ after irradiation at temperatures of 100, 350, and 600°C and at fast fluences up to 6×10^{20} n/cm², and he found little volume increase. No change of volume was observed by Walters²¹ when the beryllium was irradiated at a temperature of 600°C and at a fast fluence of 8×10^{20} n/cm². Work done by Hickman and Stevens²² and by Hickman and Chute²³ on beryllium from different sources confirmed previous findings and indicated that a decrease in

density of about 0.5 to 1% was obtained from irradiation at temperatures of 650 to 700°C with fast neutrons at a fluence of 6×10^{20} n/cm². A study by Weir²⁴ of specimens of various chemical composition and fabrication showed that irradiation to 3.6×10^{20} n/cm² (> 1 Mev) at temperatures up to 600°C and irradiation to 1.3×10^{20} n/cm² at temperatures up to 700°C did not produce appreciable swelling, but irradiation to 1.7×10^{20} n/cm² at temperatures higher than 700°C did cause swelling. Approximately 1% swelling was obtained with irradiation to 3.6×10^{20} n/cm² at a temperature of 700°C.

The swelling caused by high-temperature annealing of beryllium irradiated by fast neutrons at low temperatures has also been studied.^{25,26,27} Sections of the beryllium reflector from the MTR that had been irradiated to a fast fluence of 10^{21} n/cm² at a temperature of 70°C were annealed at temperatures of 600 to 1000°C. The results of these annealing studies are illustrated in Fig. 1.

Fig. 1. Swelling of Beryllium Irradiated to a Fast Fluence of 1×10^{21} n/cm² at a Temperature of 70°C as a Function of Annealing Time and Temperature. (from Ref. 27)

It may be observed that the threshold temperature for swelling in beryllium irradiated to a fast fluence of 1×10^{21} n/cm² is about 725°C.

These results agree with the findings of Rich, Walters, and Barnes¹⁷ in that significant swelling occurred in beryllium annealed at temperatures above 700°C following irradiation to a fluence of 1×10^{21} n/cm². The studies reported by Rich, Walters, and Barnes also showed that breakaway swelling depends not only on the annealing temperature but also on the annealing time. This is illustrated in Fig. 2. It should be noted that the swelling resulting from an annealing temperature of 800°C increases rapidly after 200 hours. The studies made by Rich, Walters, and Barnes show that after irradiation to a fast fluence of 7.6×10^{21} n/cm², the breakaway swelling temperature is 600°C, as compared with a breakaway swelling temperature of 725°C for irradiation to a fluence of 1×10^{21} n/cm².

Fig. 2. Time Dependence of Swelling for Various Annealing Temperatures for Beryllium Irradiated to a Fast Fluence of 2.75×10^{21} n/cm² at a Temperature of 70°C. (from Ref. 17)

The densities of beryllium samples irradiated at ambient conditions in the ETR and of samples cut from the beryllium lattice pieces from the MTR were determined by Tromp.²⁸ The samples were annealed in a vacuum for various periods of time at different temperatures. The swelling threshold temperature depends on the fast fluence and possibly on the mechanical properties of the specific batch of beryllium, as illustrated in Fig. 3. No data on the swelling threshold temperature for fast fluences higher than 1.6×10^{22} n/cm² are available, and it is not clear whether

Fig. 3. Swelling Threshold Temperature of Beryllium as a Function of Gas Content and Fluence. (from Ref. 28)

the threshold temperature continues to drop as the fluence increases. Further research is needed in this area.

The swelling of beryllium caused by fast neutron irradiation can be summarized as follows.

1. At irradiation or annealing temperatures below the swelling threshold temperature, the helium produced by neutron irradiation remains as a solid solution or it precipitates in the form of extremely small bubbles at the grain boundary and the resulting amount of beryllium swelling is insignificant. Thus, in applications at temperatures below the threshold temperature, beryllium retains its dimensional stability even under fast neutron irradiation.

2. The swelling threshold temperature of beryllium depends upon the fast fluence, time, and the history of the beryllium. Preliminary tests indicate that the threshold temperature decreases as the fast fluence increases. However, more research with fluences higher than 1.6×10^{22} n/cm^2 is needed to determine whether the threshold temperature continues to drop.

3. There is some temperature higher than the swelling threshold temperature at which swelling appears to increase rapidly. This breakaway swelling may cause distortion or even cracking of the beryllium structure.

Mechanical Properties

Irradiation by fast neutrons produces a marked effect on the mechanical properties of beryllium, and this effect along with the swelling effect have been the subject of numerous investigations. A fairly thorough review of the effects of radiation on beryllium was recently reported by Kangilaski.²⁹ The effects depend upon the irradiation temperature, testing temperature, fast fluence, and the fabrication technique used on the material. The mechanical properties considered by most researchers are the ultimate tensile strength, yield stress (0.1% offset), hardness, elongation, and the reduction in area. Some data on compression and bending are also available.

For testing temperatures between 20 and 700°C and for materials fabricated by different techniques, Stevens and Hickman^{22,30} reported that irradiation by a fast fluence below 5×10^{19} n/cm² at a temperature range of 75 to 100°C did not affect the tensile properties of beryllium significantly. According to Hickman and Chute,²³ irradiation by fast fluences above 5×10^{19} at a temperature range of 75 to 100°C of beryllium samples made from Pechiney electrolytic powder, direct-extruded at a temperature of 1050°C, and tested at room temperature resulted in almost a linear relationship between increasing yield strength and hardness and decreasing ductility with increasing fast fluences. These relationships are illustrated in Fig. 4.

The effect of irradiation by a fast fluence of 4×10^{20} n/cm² at a temperature of 100°C on the tensile properties of beryllium reported by Walters²¹ is illustrated in Fig. 5. The changes in tensile properties are not very significant at higher test temperatures but became more prominent at lower temperatures. The mechanism of hardening by fast neutron irradiation is believed to be caused by the interstitial and vacancy defects produced and by the transmuted helium atoms. At low testing temperatures, the helium atoms stay in the metal matrix in atom form and cause solid solution hardening. Both the helium atoms and the defects impede the movement of dislocations, thereby increasing the

Fig. 4. Changes in Yield Strength, Ductility, and Hardness of Beryllium Irradiated at Fast Fluences and a Temperature Range of 75 to 100°C. (from Ref. 23)

Fig. 5. Effect of Irradiation at a Fast Fluence of $4 \times 10^{20} \text{ n/cm}^2$ and a Temperature of 100°C on the Tensile Properties of Beryllium. (from Ref. 21)

strength and decreasing the ductility of the beryllium. At higher testing temperatures, the annealing effect occurs and the irradiation-induced changes in the tensile properties of the beryllium are reduced.

In the tests made by Rich, Walters, and Barnes,¹⁷ hot-pressed beryllium was irradiated with fast fluences of more than 10^{21} n/cm² at temperatures varying from 280 to 480°C (the detailed thermal history in the reactor was unknown). When tested in a Vicker projection microscope using a 200-g load, the hardness of the beryllium increased from 150 DPN to 220 DPN. The beryllium recovered from this hardening only after being heated at temperatures above 800°C for a period of one hour when a measurable change in density occurred. Tests of the tensile properties of the beryllium were made at room temperature and at temperatures of 300, 450, and 600°C, and the results of these tests are illustrated in Fig. 6.

Fig. 6. Tensile Properties of Beryllium Irradiated at a Fast Fluence of 3.3×10^{21} n/cm² and Temperatures Varying From 280 to 480°C. (from Ref. 17)

There is a significant increase in the ultimate tensile strength and the 0.1%-proof yield strength in these test temperature ranges, and the elongation was reduced to practically zero. Only when the test

temperature was close to 600°C did the values of the ultimate tensile and yield strengths of the irradiated beryllium approach those of unirradiated beryllium. However, the ductility of the irradiated beryllium was not recovered.

The tests made by Walters^{20,21} also show that at the intermediate irradiation temperature range of 250 to 550°C, an increasing fast fluence progressively changes the tensile properties of beryllium. The variations in the tensile properties of beryllium irradiated at fast fluences of 2×10^{20} , 6×10^{20} , and 8×10^{20} n/cm² and a temperature of 350°C and tested at a temperature range between 20 and 600°C are illustrated in Fig. 7. The decrease in the change in the yielding strength at higher temperatures was believed to be caused by annealing out of the defects produced by the fast fluence. The decrease in the recovery of ductility in the beryllium irradiated at increasing fast fluences toward the pre-irradiation ductility of the material at high test temperatures is caused by the coalescence of helium atoms into bubbles at grain boundaries. These bubbles tend to weaken the grain boundaries and to promote intergranular fracture.

In earlier work, Rich and Walters³¹ irradiated hot-pressed Pechiney powder to a fast fluence of 2×10^{20} n/cm² at a temperature of 350°C and to 6×10^{20} n/cm² at 600°C, and they tested the samples at room temperature and at 150, 300, 450, and 600°C. Irradiation at a temperature of 350°C produced hardening and loss of ductility at test temperatures below the irradiation temperature. This was caused in part by the formation of dislocation loops, but the main cause probably was dislocation pinning by helium atoms. Irradiation at a temperature of 600°C produced little change in the mechanical properties of beryllium even though gas bubbles were formed in both the grain and at boundaries. These boundary bubbles caused a change in the fracture mode from trans- to inter-crystalline at temperatures below 200°C. Some loss of ductility was observed with an increased concentration of grain boundary bubbles. Irradiation at a temperature of 350°C followed by annealing at temperatures ranging from 700 to 800°C for one hour produced a bubble concentration in the grain similar to that observed after prolonged irradiation at a temperature of

(a) FAST FLUENCE OF $2 \times 10^{20} \text{ n/cm}^2$ (b) FAST FLUENCE OF $6 \times 10^{20} \text{ n/cm}^2$ (c) FAST FLUENCE OF $8 \times 10^{20} \text{ n/cm}^2$

Fig. 7. The Effects of Irradiation at Various Fast Fluences and a Temperature of 350°C on the Tensile Properties of Beryllium. (from Ref. 21)

600°C , although post-irradiation annealing did not produce the marked grain boundary bubbling observed at the higher irradiation temperature.

It was reported by Hyam and Sumner³² that the presence of gas bubbles at grain boundaries modifies the stress behavior of beryllium irradiated to a fast fluence of $3.8 \times 10^{19} \text{ n/cm}^2$ at temperatures in the range of 450 to 700°C . Both the irradiated test specimens and the unirradiated

specimens that were annealed at irradiation temperatures for the irradiation period were strained to rupture at the irradiation temperature at a strain rate of 0.12^{-1} . It was noted that the ductility decreased with increased temperature in both the irradiated and unirradiated specimens and that the mechanism of failure was changed. Moreover, the elongation to failure at temperatures of 600 to 700°C was lower for the irradiated specimens than for the unirradiated but annealed ones. From microstructural observation of the grain boundaries, it was concluded that the stress-induced growth of bubbles resulted in the development of large cavities on the surface of the grain that linked up to form grain boundary fissures and ultimately caused failure. The observations are consistent with a mechanism of growth involving the diffusion of vacancies by the bubbles from the grain boundaries that is induced by local intergranular tensile stress. Theoretical considerations show that any stress will make grain-boundary bubbles grow to some extent, but under a stress greater than a critical value (which can be much less than the yield stress) determined by the initial size of the bubble, the bubble will continue to grow as long as the stress is applied. Once the bubble has grown by more than 73% under this applied stress, the stress required to keep it growing becomes progressively less.

Beryllium specimens fabricated by various methods were irradiated by Hickman and Bammister³³ to fast fluences of from 5.5×10^{20} to 9×10^{20} n/cm² at temperatures of 450, 550, and 650°C. Generally, the test results were in agreement with the previous observations that a considerable reduction in high-temperature ductility can occur and that this is caused by helium bubble formation at grain boundaries. Significant density changes were observed only at a temperature of 650°C. The beryllium specimens fabricated by hot pressing and extrusion showed tensile properties superior to those of the specimens fabricated by loose sintering and extrusion in both the as-received and the irradiated conditions. Pre-irradiation slow-cooling annealing did not change the properties of the hot-pressed and extruded specimens before or after irradiation. However, this annealing did improve the pre-irradiation properties of the loose-sintered and extruded specimens, although no difference was observed in the properties of these specimens after irradiation.

Another series of studies related to the effects of high-level neutron irradiation at elevated temperatures on the plastic deformation of extruded beryllium was made by Ells and Weir.³⁴ They irradiated specimens of S-260-B beryllium (warm extruded and heat treated by slow cooling from 800°C) at temperatures in the range of 250 and 430°C in the ORR and NRX reactors and performed post-irradiation tensile tests. They concluded that (1) a fast fluence of 1.4×10^{19} n/cm² at a temperature of 250°C increases the yield stress significantly but has no effect on the ductility or work-hardening coefficient of the beryllium, (2) a fast fluence of 10^{21} n/cm² at a temperature of 430°C reduces the ductility of beryllium and this reduction is particularly severe for test temperatures lower than 200°C, (3) the ultimate strength of beryllium is independent of irradiation up to a fast fluence of 10^{21} n/cm² at all test temperatures from room temperature to 600°C, and (4) fast fluences in the range of 1.4×10^{19} to 10^{21} n/cm² strongly promote the development of double yield points and multiple yielding. It is believed that the yield points developed in irradiated beryllium are caused by dislocation pinning by small bubbles or individual helium atoms. It was also observed that after the stress in the beryllium irradiated in the temperature range of 250 to 430°C has passed the yield strength of the material, the helium has little further effect on plastic deformation at test temperatures up to 600°C. Finally, if the irradiation and heat treatments after irradiation do not result in bubble formation at grain boundaries, the fracture mode is not affected by irradiation.

Irradiation at or above a temperature of 600°C results in tensile property changes in some batches of beryllium but not in others. Rich and Walters³¹ reported no significant change in the yield stress and elongation of specimens irradiated to 6×10^{20} n/cm² at a temperature of 600°C, while Walters¹⁹ and Hickman and Bannister³³ observed changes in the specimens they tested. This discrepancy can be explained by the fact that impurity sites act as traps for helium atoms and prevent them from agglomerating into bubbles at the grain boundaries. Also, the point defects produced by fast neutrons would probably be annealed out at temperatures above 600°C.

Only limited work has been done with respect to the effects of irradiation on the tensile properties of extruded beryllium specimens formed transverse to the extrusion direction. Rich and Walters³¹ performed a few tensile tests on such hot-pressed and hot-extruded specimens that had been irradiated at a fast fluence of 2×10^{20} n/cm² and a temperature of 350°C and at 6×10^{20} n/cm² and 600°C. The results of their tests illustrated in Fig. 8 did not indicate that the irradiation had any

Fig. 8. The Effects of Irradiation on the Transverse Mechanical Properties of Extruded Beryllium. (from Ref. 31)

significant effect on the transverse tensile properties. However, it should be noted that even in an unirradiated condition, beryllium is extremely brittle in the transverse direction.

A mathematical model was developed by Barnes¹⁸ to predict changes in the yield strength of beryllium caused by irradiation. The model is based on the number and size of helium bubbles in the material and on the assumption that these bubbles impede the movement of dislocations in the matrix. As related to bubble size and number, the yield strength of the irradiated material

$$\sigma_i = \sigma_u + Gb(2Nr)^{1/2},$$

where

σ_u = yield strength of unirradiated material,

G = shear modulus,

b = Burger's vector,

N = number of bubbles per cm^3 ,

r = radius of the bubbles.

This relationship was used by Walters²⁰ for comparison with results obtained experimentally, and the results of this comparison are given in Table 3. It should be pointed out that the computational method of determining the yield strength based on bubble size and number is very applicable as long as the bubbles are visible and have diameters larger than 100 $\text{\AA}$. When extrapolated to include small bubbles with diameters of 30 and 10 $\text{\AA}$, the theoretical prediction of change in yield strength is not as good, even though the calculated value still has the same order of magnitude as the experimental value.

Tests of the effects of annealing on irradiated beryllium have not been carried out systematically. The results of tests made by Walters²¹ on the effects of annealing on the room-temperature longitudinal yield stress of Pechiney beryllium irradiated to a fast fluence of 8×10^{20} n/cm^2 at a temperature of 350°C are illustrated in Fig. 9. The effect of annealing on the hardness, yield stress, and elongation of hot-pressed Brush Company beryllium irradiated to a fast fluence of more than 10^{21} n/cm^2 at temperatures between 280 and 480°C and tested at a temperature of 450°C by Rich, Walters, and Barnes¹⁷ is illustrated in Fig. 10. The

Table 3. Calculated Values of Yield Stress in Irradiated Beryllium Compared With Actual Experimental Values (from Ref. 20)

Irradiation at		Post-Irradiation Annealing		Yield Strength Calculated From Bubble Counts (psi)	Unirradiated		Calculated Plus Unirradiated Yield Strength (psi)	Actual Irradiated	
Fast Fluence (n/cm ²)	Temperature (°C)	Time (hr)	Temperature (°C)		Yield Strength (psi)	Test Temperature (°C)		Yield Strength (psi)	Test Temperature (°C)
2 x 10 ²⁰	350	1	600	5,080	35,000	20	40,080	44,300	20
2 x 10 ²⁰	350	1	1000	6,420	35,000	20	41,420	37,000	20
6 x 10 ²⁰	350	1	800	12,970	35,000	20	47,970	41,700	20
6 x 10 ²⁰	350	1	900	8,530	35,000	20	43,530	41,100	20
6 x 10 ²⁰	350	1	1000	15,790	35,000	20	50,790	45,600	20
6 x 10 ²⁰	600			5,080	35,000	20	40,080	40,000	20
1.5 x 10 ²¹ a	280 - 450			35,900	16,800	300	52,700	53,600	300
1.5 x 10 ²¹ a	280 - 450	1	900	14,370	12,700	450	27,070	28,500	450
1.5 x 10 ²¹ a	280 - 450	1	950	8,420	12,700	450	21,120	20,800	450

^aHot-pressed beryllium

Fig. 9. The Effects of Annealing on the Room-Temperature Longitudinal Yield Stress of Pechiney Beryllium Irradiated to a Fast Fluence of 8×10^{20} n/cm² at a Temperature of 350°C. (from Ref. 21)

Fig. 10. The Effect of Annealing on the Hardness, Yield Stress, and Elongation of Beryllium Irradiated to a Fast Fluence of More Than 10^{21} n/cm² at Temperatures Between 280 and 480°C. (from Ref. 17)

recovery of the room-temperature yield strength with annealing in Pechiney hot-pressed and extruded beryllium irradiated to 3.4×10^{20} and 6×10^{20} n/cm^2 at temperatures between 70 and 100°C reported by Stevens and Hickman³⁰ is illustrated in Fig. 11, and the recovery of ductility in the same test is shown in Fig. 12.

Fig. 11. Recovery of Yield Strength With Annealing in Pechiney Hot-Pressed Extruded Beryllium Irradiated to 3.4×10^{20} and 6×10^{20} n/cm^2 at Temperatures Between 70 and 100°C . (from Ref. 30)

Fig. 12. Recovery of Ductility With Annealing in Pechiney Hot-Pressed and Extruded Beryllium Irradiated to 3.4×10^{20} and 6×10^{20} n/cm^2 at Temperatures Between 70 and 100°C . (from Ref. 30)

It may be noted from observation of Figs. 9 through 12 that the annealing temperatures at which significant removal of the irradiation induced change in hardness, yield strength, and ductility takes place are almost the same. This annealing temperature of above 700°C is about the same temperature at which significant swelling in irradiated beryllium begins. Most researchers believe that at this annealing temperature, the restoration of pre-irradiation properties is brought about by the removal of defect clusters and small helium bubbles that act as barriers to dislocation movement in the irradiated material. When the defect clusters are removed and the helium bubbles reach a significant size, no further obstacles are offered to dislocation movement and the pre-irradiation mechanical properties of the beryllium are restored. The restoration of ductility is explained in terms of bubble migration to the grain boundary that allows more elongation to take place in the grain itself before failure. However, the effects of annealing on irradiated beryllium vary with different batches of material since almost all batches have some variation in mechanical properties.

Compression tests were performed by Beeston^{35,36} on irradiated beryllium, and the results of tests made on samples irradiated to different fast fluences at a temperature of 70°C are given in Table 4. As the fast fluence is increased from 0.6×10^{21} to 5×10^{21} n/cm², the compressive yield strength (0.2% offset) increases from 79,000 to 163,000 psi and the ductility decreases. The ultimate compressive strength reaches a peak after irradiation to a fast fluence of 1.6×10^{21} n/cm², and it then decreases with further increases in the fast fluence. As given in Table 5, the results of tests on beryllium samples irradiated to various fast fluences at temperatures of 600 and 750°C indicate only minor changes in the compressive properties. These results are in agreement with tensile test data on beryllium irradiated at the same temperature.

Some bending tests were made by Weir²⁴ on beryllium specimens that were irradiated to a fast fluence of 1.3×10^{20} n/cm² at temperatures of 500 to 700°C and to 6×10^{20} n/cm² at 60°C. The results of these tests given in Table 6 indicate no change in the fracture load and deflection

Table 4. Compression Strength of Beryllium Samples Irradiated to Various Fast Fluences at 70°C (from Ref. 35)

Position Code ^a	Fast Fluence ^b (n/cm ²)	Compression Yield Strength, 0.2% Offset (1000 psi)	Compression Ultimate Strength (1000 psi)	Total Strain in 1.5 in. (%)	Plastic Strain in 1.5 in. ^c (%)
LL-6-7-8-9 (4 samples)	0.6×10^{21}	79 ± 4	153 ± 62	14.4	12.9
LT-6-7-8-10 (4 samples)	1.1×10^{21}	98 ± 4	184 ± 16	11.5	11.0
LL-1-2-3 (3 samples)	1.6×10^{21}	117 ± 6	194 ± 13	13.9	12.4
LT-3-4-5 (3 samples)	3.2×10^{21}	122 ± 24	129 ± 41	3.1	1.5
MT-6	5.0×10^{21}	163	163	2.8	0.7

^aAverage of number of samples indicated.

^bCalculated from fluence profiles of MTR Cycle 146 for various positions in which LB-15 received irradiation (approximate values).

^cMeasured from yield point to point of fracture.

Table 5. Mechanical Properties of As-Received and Irradiated Beryllium Samples Tested in Compression (from Ref. 36)

Material	Yield Strength, 0.2% Offset (1000 psi)	Ultimate Strength (1000 psi)	Plastic Strain ^a (%)
As-received samples	44.0 ^b	191.7	30.1
Capsule 1, control samples ^c (600°C, 3532 hours, 105 cycles)	46.4	210.1	30.7
Capsule 2, control samples (750°C, 1589 hours, 55 cycles)	47.0	212.0	26.5
Capsule 3, control samples (600°C, 1992 hours, 52 cycles)	51.2	184.5	27.8
Capsule 6, 600°C, 3559 hours (irradiated to 1.08×10^{21} n/cm ²) ^d	48.5	147.9	19.6
Capsule 7, 750°C, 1586 hours (irradiated to 0.75×10^{21} n/cm ²)	49.3	147.1	19.9
Capsule 8, 600°C, 1973 hours (irradiated to 0.88×10^{21} n/cm ²)	64.9	174.7	25.2

^aPlastic strain was calculated as the strain at the fracture point minus the strain at the yield point.

^bAll values are averages of three measurements.

^cControl samples were heated at temperatures and times indicated and thermally cycled the number of cycles equivalent to reactor scrams and shut downs.

^dAll fluence values are for neutron energies > 1 MeV.

Table 6. Bending Properties of Irradiated Beryllium (from Ref. 24)

Specimen	Fluence (10^{20} n/cm ²)	Irradiation Temperature (°C)	Pre-irradiation ^a		Post-irradiation	
			Load (lb)	Deflection (mils)	Load (lb)	Deflection (mils)
HPB	1.3	500	79 to 92	5.0 to 6.5	74	5.1
HPB	1.3	600	79 to 92	5.0 to 6.5	96	4.6
CR	1.3	500	60 to 75	1.5 to 2.5	66	2.0
CR	1.3	560	60 to 75	1.5 to 2.5	76	2.0
CR	1.3	700	60 to 75	1.5 to 2.5	51	1.9
			Post-irradiation		Post-anneal	
HPB ^b	6	60	48	1.1	71	9.1
HPB ^c	6	60	41	0.9	95	3.2
CR ^d	6	60	44	1.0	57	1.5
CR ^e	6	60	38	1.0	52	2.6
CR ^f	6	60	60	1.1	69	1.5
CR ^g	6	60	57	1.2	100	2.6
CR ^h	6	60	28	0.7	62	2.2

^aThese values are ranges of five determinations.

^bAnnealed at 700°C for 1 hr.

^cAnnealed at 800°C for 1 hr.

^dAnnealed at 400°C for 1 hr.

^eAnnealed at 500°C for 1 hr.

^fAnnealed at 600°C for 1 hr.

^gAnnealed at 700°C for 1 hr.

^hAnnealed at 800°C for 1 hr.

of the specimens irradiated to 1.3×10^{20} n/cm² at temperatures of 500 to 700°C. This is in agreement with tensile test data in the same temperature range. Some decrease in ductility was exhibited by the specimens irradiated to a fast fluence of 6×10^{20} n/cm² at a temperature of 60°C, but this ductility was recovered upon annealing at a temperature of 400°C for one hour. However, these results do not agree with those obtained by Rich, Redding, and Barnes.¹⁶

The specimens tested by bending by Rich, Redding, and Barnes were irradiated to a fast fluence of 7.6×10^{21} n/cm² at a temperature of 70°C and tested at room temperature and at temperatures of 300, 600, and 700°C.

The results of their tests indicated that no significant change in bending strength is produced by neutron irradiation. However, changes in ductility are apparent. None of the irradiated samples showed any bending before fracture, whereas a small amount of deflection was observed in the unirradiated specimens before fracture at each test temperature. All of the irradiated specimens were annealed at the testing temperature for 17 hours before the test, and even the 700°C annealing temperature was not sufficient for recovery of pre-irradiation ductility. It was thought that the eventual formation of large bubbles at the grain boundary caused some embrittlement. It may be seen from these two series of experiments that there are variations in the mechanical property changes in beryllium caused by irradiation and annealing.

The neutron irradiation effects on the mechanical properties of beryllium may be summarized as follows.

1. Irradiation by fast fluences up to 5×10^{19} n/cm² at a temperature range of 75 to 100°C did not affect the tensile properties of beryllium fabricated by different techniques when tested at temperatures between 20 and 700°C. For fast fluences above 5×10^{19} n/cm², the increase in the tensile and 0.1%-offset yield strengths and the decrease in ductility become more significant as the fast fluence is increased. The resulting effects depend upon the test temperature and the material itself. The changes in tensile properties are more prominent at lower test temperatures. Because some annealing effect takes place at higher temperatures, the amount of change is reduced.

2. Irradiation of beryllium specimens to a fast fluence of 4×10^{19} n/cm² at an intermediate temperature range of 210 to 350°C did not cause a significant change in the tensile properties but a more pronounced reduction in ductility when tested at temperatures between 100 and 600°C in some cases. In other cases, irradiation to a fast fluence of 1.4×10^{19} n/cm² at a temperature of 250°C caused an increase in the yield stress but little change in ductility.

3. Irradiation by fast fluences from 2×10^{20} to 3.3×10^{21} n/cm² in the intermediate temperature range of 280 to 480°C produced significant changes in the tensile and yield strengths of beryllium specimens and a

drastic reduction in ductility when tested at temperatures between 100 and 600°C in many cases. This reduction in ductility was more severe for test temperatures lower than 200°C. As the test temperature was raised to approach or pass 600°C, the tensile and yield strengths approached pre-irradiation values but the ductility was not quite recovered. The changes in tensile and yield strength decreased with increasingly higher test temperatures, and this was believed to be caused by the annealing effect. The recovery of ductility at higher test temperatures decreased when the fast fluence was increased because of the development of bubbles at grain boundaries that promote intergranular fracture.

4. Irradiation from 2×10^{20} to 6×10^{20} n/cm² at a temperature of 350°C followed by annealing at 700 to 800°C for one hour produced a concentration of bubbles in the grains similar to that observed after prolonged irradiation at a temperature of 600°C, but the grain boundary bubbling was not as marked as that produced at the higher irradiation temperature.

5. The presence of gas bubbles at grain boundaries modifies the behavior of irradiated beryllium under stress at elevated temperatures over the range of 450 to 700°C. The stress-induced growth of bubbles results in the development of larger bubbles on grain surfaces that link up to form grain boundary fissures and ultimately cause failure. The critical stress causing growth of a grain-boundary bubble was less than the yield stress of the material.

6. Irradiation to fast fluences of 5.5×10^{20} to 9×10^{20} n/cm² at a temperature range of 450 to 600°C caused considerable reduction in ductility of beryllium specimens. Above 600°C, similar neutron irradiation resulted in changes in the tensile properties of some batches of beryllium but not in others.

7. Investigation of the irradiation effects of fast neutrons on the mechanical properties of extruded beryllium transverse to the extrusion direction has been limited. The results of a few tests indicate that irradiation to a fast fluence of 2×10^{20} n/cm² at a temperature of 350°C and to 6×10^{20} n/cm² at 600°C did not cause a significant change in the transverse tensile properties of the specimens.

8. No systematic tests related to the effects of annealing irradiated beryllium have been conducted. From observation of results reported by different sources, a significant recovery of irradiation-induced changes in hardness, yield strength, and ductility takes place at annealing temperatures above 700°C . This annealing temperature is about the same temperature at which significant swelling in irradiated beryllium begins.

Thermal Conductivity

The effects of neutron irradiation on the thermal conductivity of beryllium in nuclear applications are of interest to the designer. However, research in this area has been rather limited. The measurement of thermal conductivity at low temperatures is very time consuming and expensive, but by using the established relationship between electrical resistivity and thermal conductivity, the effect of neutron irradiation on thermal conductivity can be estimated from the change in electrical resistance. Such an estimate has been reported by Dienes and Damask,³⁷ who stated the following conclusions.

1. The thermal and electrical conductivities of beryllium with impurities of a few tenths of a percent are controlled by the scattering of those impurities. The Wiedeman-Franz³⁸ law is obeyed for such cases, and the temperature dependence is typical of impurity dominated transport properties. That is, at very low temperatures, the electrical resistivity is independent of temperature but the thermal conductivity increases nearly linearly with increasing temperature.

2. Since the Wiedeman-Franz ratio is applicable, the change in the thermal conductivity of beryllium resulting from radiation damage is calculable from the known damage to the electrical conductivity. For a fast fluence of 10^{19} n/cm², the decrease in electrical conductivity is 0.031 w/cm²·°K at a temperature of 20°K and 0.047 w/cm²·°K at a temperature of 30°K. These are measurable but probably unimportant decreases in actual practice. As indicated in Fig. 13, the radiation damage at higher temperatures is less because of annealing. The arrows in Fig. 13 indicate the magnitude and direction of the radiation-induced changes.

Fig. 13. Calculated Change in Electrical and Thermal Conductivity of Impure Beryllium Upon Irradiation to a Fast Fluence of 10^{19} n/cm². (from Ref. 37)

3. When the irradiated beryllium is warmed to a temperature of 250°K, there is a rapid and complete annealing of the neutron-induced change in electrical resistivity and therefore of the associated change in thermal conductivity.

It is not clear what effect irradiation at higher fast fluences would have on the thermal conductivity of beryllium or whether annealing would have the same effect at higher fast fluences.

4. DESIGN CONSIDERATIONS IN THE USE OF BERYLLIUM

The relatively high modulus of elasticity and the low density of beryllium make its use in some structural applications very attractive. The main limitations on the usefulness of beryllium in this respect are imposed by its lack of ductility in certain temperature ranges and its toxicity. Both of these factors also contribute to the high cost of fabricating beryllium components. Because of its relatively high neutron-scattering cross section and low neutron-absorption cross section, beryllium has been used as the reflector material in many testing and high-flux research reactors. The design considerations related to the use of beryllium as a structural material and as a reflector and moderator material in nuclear reactor applications are discussed in this chapter.

Structural Material

The mechanical properties of beryllium provide the basis for its use as a structural material. However, these properties are affected by a number of parameters such as the method of production, BeO content, direction of testing with respect to the processing orientation, strain rate, temperature, and the irradiation received, which was discussed in the previous chapter of this report. There is a large quantity of information in the literature concerning the mechanical properties of beryllium under different conditions, and an extensive collection of such information with design data was published by Crawford and Burns.¹¹ Information related to the mechanical properties of reactor-grade beryllium at elevated temperatures has been reported by O'Rourke et al.,³⁹ and some of this information is also reported by White and Burke,¹ Darwin and Buddery,² and by Hausner.³

Tensile Properties

Hot-pressed QMV beryllium blocks are commonly used in nuclear and other applications, and some of the typical variations in the tensile properties of this beryllium with temperature and BeO content obtained by Jacobson and Almeter⁴⁰ from short-time tensile tests at temperatures of 70 to 1600°F (20 to 870°C) are illustrated in Figs. 14, 15, and 16. The tensile and yield strengths of the hot-pressed QMV beryllium generally decreased with increasing temperature, but an increase in strength was noted at a temperature of 800°F (425°C) for material with a low BeO content. Below a temperature of 800°F, the yield strength first decreased with an increase in BeO and then it increased. However, the BeO content has little effect on the yield strength at temperatures above 800°F. The ultimate tensile strength increased with increasing BeO content except at the point where the temperature was 800°F and the BeO content was 1.2%. At this point, the ultimate tensile strength was at a minimum. The elongation rose to a maximum at a temperature of 800°F, decreased as the temperature was increased to 1400°F (760°C), and again increased as the temperature was increased to 1500°F (815°C). The increase in ductility

Fig. 14. Ultimate Tensile Strength of Hot-Pressed QMV Beryllium as a Function of Temperature and BeO Content. (from Ref. 40)

Fig. 15. Yield Strength of Hot-Pressed QMV Beryllium as a Function of Temperature and BeO Content. (from Ref. 40)

Fig. 16. Elongation of Hot-Pressed QMV Beryllium as a Function of Temperature and BeO Content. (from Ref. 40)

at temperatures above 1400°F was particularly evident for materials with low BeO content, but it was not evident when the BeO content reached 2%. Below a temperature of 800°F , the maximum ductility was observed when the BeO content was from 1.0 to 1.2%. The BeO content did not affect the ductility significantly at temperatures from 900 to 1400°F , but the ductility decreased with an increasing BeO content at a temperature of 1400°F .

The tensile modulus of elasticity is affected by temperature, strain rate, BeO content, and many other parameters. The variations in the tensile modulus of elasticity of vacuum hot-pressed beryllium with BeO content and temperature for given strain rates reported by O'Rourke et al.³⁹ are illustrated in Figs. 17 and 18. For temperatures below 800°F, the

Fig. 17. Effect of Temperature and BeO Content on the Tensile Modulus of Elasticity of Vacuum Hot-Pressed Beryllium at a Strain Rate of 0.0002 in./in.·min. (from Ref. 39)

Fig. 18. Effect of Temperature and BeO Content on the Tensile Modulus of Elasticity of Vacuum Hot-Pressed Beryllium at a Strain Rate of 0.005 in./in.·min. (from Ref. 39)

tensile modulus of elasticity has a fairly constant value of about 43×10^6 psi for different strain rates and BeO contents. The thermal stress induced by temperature difference would be significant in this temperature range, but because of the lack of ductility in this range, there is little chance for the thermal stress to be relaxed from plastic deformation.

Yield and Fracture in a Biaxial Stress Field

The predominant mode of beryllium fracture at room and low temperatures reported by Crawford and Burns¹¹ is cleavage of the basal planes of the closely packed hexagonal space lattice of atoms in the crystal structures. In design analyses of beryllium blocks with random grain orientations, the maximum normal tensile stress criterion is used to predict fracture in the first quadrant and in parts of the second and fourth quadrants of the biaxial stress plane illustrated in Fig. 19. The maximum

Fig. 19. Composite Biaxial Yield and Fracture Criteria for Hot-Pressed Beryllium Blocks at Low Temperatures. (from Ref. 11)

normal tensile stress criterion is applicable only when cleavage is the predominant mode of fracture, and in cases where fracture by cleavage is not possible, such as in simple compression, shear is the only mode of deformation that can exist. Accordingly, the maximum shear stress criterion should be used in combination with the maximum normal stress criterion to predict fracture, as illustrated by the solid lines in Fig. 19. Yielding will precede fracture and may be predicted by using the maximum shear strain energy criterion, as indicated by the ellipse shown in Fig. 19. The coordinate axes in Fig. 19 are the principal biaxial stresses σ_1 and σ_2 , and the failure criteria are formulated as follows.

For the maximum normal tensile stress criterion,

$$\sigma_1 = F_{tu}$$

and

$$\sigma_2 = F_{tu},$$

where F_{tu} = the ultimate tensile stress.

For the maximum shear stress criterion,

$$\sigma_1 - \sigma_2 = \pm 2F_{su} \text{ in Quadrants II and IV}$$

and

$$\sigma_1 = \pm 2F_{su} \text{ and } \sigma_2 = \pm 2F_{su} \text{ in Quadrants I and III,}$$

where F_{su} = the ultimate shear stress.

For the maximum shear strain energy criterion,

$$\left(\frac{\sigma_1 - \sigma_2}{2}\right)^2 + \left(\frac{\sigma_1}{2}\right)^2 + \left(\frac{\sigma_2}{2}\right)^2 = 2(F_{sy})^2,$$

where F_{sy} = the shear yield strength.

As the temperature is increased, the shear fracture criteria shown in Fig. 19 may be considered to decrease in amplitude while the cleavage fracture criterion increases. Thus, at some temperature between 400 and 900°F, the criteria for shear failure would be almost completely operative with the criterion for cleavage fracture outside the shear criteria, as illustrated in Fig. 20. At temperatures above the equicohesive temperature (about 900°F), both yield and fracture are expected to obey the maximum shear stress criterion, as shown in Fig. 21, because of the viscous nature of grain boundary deformation. Some small amount of strain hardening is expected at temperatures above the equicohesive temperature,

Fig. 20. High-Temperature Yield and Fracture Criteria in Biaxial Stress Field. (from Ref. 11)

Fig. 21. Intercrystalline Yield and Fracture Criteria in Biaxial Stress Field. (from Ref. 11)

and this is indicated by the difference in the amplitudes of the two criteria illustrated in Fig. 21.

It should be noted that compressive yield is characteristically lower than tensile yield for hot-pressed beryllium blocks with random grain orientation. This effect may be explained as the result of twinning at temperatures below the equicohesive temperature, but the cause at temperatures above the equicohesive temperature is not clear. In either case, the effect encumbers the application of the idealized theories of material failure that have been presented. Engineering judgment is therefore a very important factor in design analysis.

No data on triaxial stress conditions are available, but from the fact that beryllium is rather brittle, it is believed that the three criteria of failure extended to three-dimensional cases can be used for design analyses of beryllium blocks with random grain orientations. There is a preferred grain orientation for cross-rolled beryllium sheet,

and the approach used to analyze the biaxial state of stress in such sheets is detailed by Crawford and Burns.¹¹

Fatigue

The results of early fatigue tests made on beryllium are reported in Chapter 7 of Ref. 2, and the results of direct tests on sheet specimens are illustrated in Fig. 22. The Sample A sheet was rolled

Fig. 22. Fatigue Test Results for QMV Beryllium Sheet Made By Unidirectional and Cross Rolling. (from Ref. 2)

unidirectionally from standard vacuum hot-pressed QMV powder and had a grain size (18 microns) about the same as that of hot-pressed block. The Sample B sheet was made from QMV powder by vacuum hot pressing, hot extruding to a flat 1/2 in. thick (20:1 reduction at 1066°C), and hot rolling at a temperature of 760°C down to 0.064 in. when the grain size was between 11 and 12 microns.

Tests were made by personnel of the Wright Air Development Division to determine the general characteristics of notched and unnotched specimens of both hot-pressed and hot-extruded beryllium under fatigue loading conditions.⁴¹ The S-N curves resulting from the series of axial fatigue tests reported by Crawford and Burns¹¹ made on hot-pressed beryllium blocks at room temperature are shown in Fig. 23. The axial fatigue

Fig. 23. Axial S-N Curves for Hot-Pressed Beryllium Block at Room Temperature When $R = 0.2$. (from Ref. 11)

characteristics of the hot-pressed blocks were determined as a function of various combinations of the stress concentration factor, K_t , and the stress ratio R , where $R = \text{minimum stress}/\text{maximum stress}$. The S-N curve for hot-pressed beryllium block at a temperature of 1100°F when $R = 0.2$ is shown in Fig. 24. A testing frequency of approximately 350 cps was used to obtain the data at both room temperature and at 1100°F. The curve illustrated in Fig. 24 shows a considerable scattering of data for unnotched specimens, and the notch did not appear to have too much effect on the test results at the higher temperature. The results of axial fatigue tests made on the same material at a temperature of 1100°F when $R = -1$ are shown in Fig. 25. It may be seen that by reversing the stress, the fatigue behavior of the hot-pressed beryllium followed the usual S-N curve shape.

Fig. 24. Axial S-N Curve for Hot-Pressed Beryllium Block at a Temperature of 1100°F When $R = 0.2$. (from Ref. 11)

Fig. 25. Axial S-N Curves for Hot-Pressed Beryllium Block at a Temperature of 1100°F When $R = -1$. (from Ref. 11)

A more complete picture of the relationship between mean stress, alternating stress, and the cycles to failure for axial fatigue in unnotched hot-pressed beryllium block at room temperature is illustrated in Fig. 26. The alternating stress = maximum stress - mean stress.

Fig. 26. Effect of Mean Stress on the Axial Fatigue Behavior of Unnotched Hot-Pressed Beryllium Block at Room Temperature. (from Ref. 11)

Some information on the fatigue characteristics of different fastener joints is also reported by Crawford and Burns,¹¹ and the results of limited tests on hot-upset beryllium sheets and on beryllium extrusions are presented.

Notch Sensitivity

When beryllium is used as a structural material, the designer must have knowledge of the sensitivity of the material to notches or other geometric discontinuities that cause stress concentrations. Although beryllium is known to be lacking in ductility, the reduction in the ultimate strength of notched specimens demonstrated the existence of a certain redistribution of stresses at the root of the notch caused by plastic deformation. This phenomenon is expressed as notch sensitivity, and information on the notch sensitivity of beryllium is rather limited.

Tests were made to determine the notch sensitivity characteristics of beryllium hot-pressed blocks and cross-rolled sheet, and the results of these tests were reported by Crawford and Burns.¹¹ Data on the notch sensitivity of QMV hot-pressed beryllium block with a BeO content of

1.55% at different temperatures are illustrated in Fig. 27, and data on cross-rolled beryllium sheet with a BeO content of 1.75% are shown in

Fig. 27. Notch Sensitivity of QMV Hot-Pressed Beryllium Block With a BeO Content of 1.55%. (from Ref. 11)

Fig. 28. It may be seen from these illustrations that hot-pressed block and cross-rolled sheet are somewhat notch sensitive at temperatures from room temperature up to 500°F, although the beryllium is no more sensitive than high-strength steels and titanium alloys. Above a temperature of 500°F, neither form of beryllium is notch sensitive.

The notch sensitivity characteristic of block beryllium at room temperature is due chiefly to the fact that basal plane cleavage is the predominant mode of fracture for the block material at room temperature. Basal plane cleavage is accompanied by a reduction in ductility and Poisson's ratio. This inhibits the development of biaxial stresses at the base of the notch. Even if biaxial tension were developed, biaxial strengthening does not occur when basal plane cleavage is the predominant mode of failure. At temperatures above 800°F, shear of prism planes of the closely packed hexagonal lattice structure of beryllium is the predominant mode of failure and biaxial strengthening can and does

Fig. 28. Notch Sensitivity of Cross-Rolled Beryllium Sheet With a BeO Content of 1.75%. (from Ref. 11)

occur. The high notch-to-strength ratio exhibited at a temperature of 1100°F may possibly be explained by the fact that the fractures were entirely intergranular, while fracture at the lower temperatures was mainly transgranular. Perhaps large values of Poisson's ratio under somewhat viscous action at this temperature led to triaxial tension over much of the area between notch bases, and this could account for the apparent strengthening.

The cross-rolled beryllium sheet has a highly oriented grain structure and is therefore expected to follow a failure pattern that is different than the one of hot-pressed blocks. The C axes of the lattice structures composing the grains are oriented normal to the plane of the sheet. Accordingly, the basal planes of the lattice structures on which low-temperature fracture occurs in the block material are parallel to the direction of the loading in the sheet specimens. Further,

Poisson's ratio is virtually zero in the C direction, while it is about 0.10 in the elastic range in planes normal to the C direction. Thus, the stress at the base of the notch is essentially uniaxial, while it is slightly biaxial in the plane of the specimens toward the center from the notches.

In view of these considerations, the high notch sensitivity of cross-rolled beryllium sheet at low temperatures appears to be the result of brittle fracture in the area somewhat inward from the notch base where the stresses are biaxial but close enough to the notch base to be in the area of high stress concentrations. At the base of the notch, the stresses are essentially uniaxial and would be relieved by ductility. At elevated temperatures, the high stress concentration at the notch base could be relieved by the increased ductility, and the increased Poisson's ratio in the width direction of the specimen also leads to biaxial strengthening. At a temperature of 1100°F, the fracture mode exhibited by the notched sheet specimens was predominantly transgranular, while the fracture mode exhibited by the block specimens was predominantly intergranular. The notch strengthening effect applies to this case as well. Rolling apparently causes the grain boundaries to lie chiefly in the plane of the sheet, and this reduces the stress on the grain boundaries and inhibits intergranular fracture.

Buckling

Because of its high modulus of elasticity, beryllium has a higher elastic stability than most metals. Conventional design procedures for compression members can be used where beryllium is a structural member, but it must be recognized that beryllium exhibits a catastrophic post-buckling failure mechanism at room temperature and in the low temperature range. Appropriate margins of safety must therefore be imposed for different applications. Data are reported by Crawford and Burns¹¹ to assist in the structural design of beryllium components. This information includes buckling and post-buckling design data for flat unstiffened panels in compression and shear; design data on column buckling and

crippling; and design data on the buckling of monocoque cylinders caused by axial compression, torsion, and hydrostatic or radial pressure.

Minimum Weight Design

The main advantage in the use of beryllium over other structural materials in many applications is its light weight. Nondimensional minimum-weight design procedures for wide columns, compression panels, shear panels, multiweb box beams, axially loaded cylinders, cylinders in torsion, and hydrostatically compressed cylinders are reported by Crawford and Burns.¹¹

Nuclear Reactor Material

Beryllium has been used as the reflector material in many testing and high-flux research reactors because of its relatively high neutron-scattering cross section and low neutron-absorption cross section. Beryllium also has the potential for use as a solid moderator material, but its high cost when compared with that of graphite has limited such use. The effects of neutron irradiation on beryllium and the general design considerations related to the mechanical properties of beryllium as a structural material have already been discussed. The design considerations related to radiation damage, thermal stress, neutron absorption, corrosion, and mechanical loading of beryllium in nuclear applications are discussed in the following paragraphs.

Swelling Caused by Fast Neutron Irradiation

Most reports of research done on beryllium swelling caused by fast neutron irradiation in the literature reviewed state that for fast fluences up to about 2×10^{22} n/cm² at temperatures below 550°C there was no "significant" swelling observed in reactor-grade beryllium. However, in most cases, "insignificant" swelling denoted a volume or

density change of less than 1%. When one considers the fact that the modulus of elasticity of beryllium remains at approximately 40×10^6 psi at a moderate temperature range (below 600°C), even a small volume change of 0.1%, which corresponds to a linear change of 0.033%, would produce a stress in the order of 13,000 psi if one-dimensional restraint is considered. This stress level is not low when compared with the strength of beryllium.

The amount of beryllium swelling depends upon the fast fluence received. When the neutron exposure rate varies in accordance with the location of the reflector or moderator material, the difference in swelling in various portions of the reflector or moderator is likely to induce internal stress similar to thermal stress. The combined stress caused by swelling, thermal effects, and possibly mechanically induced stress could cause distortion or even cracking of the beryllium reflector or moderator. Several attempts have been made to treat irradiation-induced stress as the equivalent of thermal stress in cylindrical rods,^{42,43} but unfortunately there is little available information that gives the detailed relation between volume change, temperature, and fast fluence for beryllium.

The designer must still use the rather limited results from the not fully controlled ORR and MTR tests as a rather rough guide when considering beryllium swelling caused by fast neutron irradiation. It is not clear whether the threshold temperature for swelling, illustrated in Fig. 3, continues to drop with fast fluences above 2×10^{22} n/cm², and more research is needed to form a design basis for swelling considerations. It is felt that the design for a replaceable inner section reflector, as used in the HFIR,⁴⁴ is a good scheme under the present circumstances. It is hoped that information obtained from the HFIR experiments will be helpful in future designs of beryllium reflectors and moderators.

Reduction in Ductility Caused by Fast Neutron Irradiation

Irradiation by fast neutrons reduces the already low ductility of beryllium significantly. The low ductility of beryllium before irradiation limits its application, but the further reduction in ductility in

some nuclear applications must also be considered. The low ductility will not permit the relaxation of local stresses produced by swelling and thermal effects, and this may produce some of the cracking of beryllium shim rods and reflectors experienced in test reactors.

Thermal Stress

Beryllium has a rather limited ductility in the hot-pressed form, which is usually used in reactor applications. As discussed in the preceding paragraph, irradiation at fast fluences further reduces the ductility of beryllium, and thermal stress becomes one of the main causes of distortion and cracking of beryllium reflectors. The ultimate tensile strength for unirradiated beryllium was given as about 28,000 psi and that for beryllium irradiated to a fast fluence of 3.3×10^{21} n/cm² was about 53,000 psi.¹⁷ However, the modulus of elasticity remains at about 40×10^6 psi at temperatures below 600°C. Moderate temperature differences at different portions of the reflector induce a rather high thermal stress, and this added to the stress induced by swelling caused by irradiation can easily approach the limiting stress level. The combined thermal- and swelling-induced stress is not likely to be relieved because of the lack of plastic flow, and the danger of cracking is obvious.

Even though beryllium has fairly good thermal conductivity, it also has a coefficient of thermal expansion close to that of steel, as given in Table 2. Therefore, good cooling must be provided to limit the thermal stress, and the heat transfer and heat generation rates must be considered carefully. Because of the lack of research data, the design thermal stress for beryllium reflectors in some applications has been limited to 12,000 to 15,000 psi.⁴⁴

Neutron Absorption

The life of the fuel element depends greatly upon the neutron absorption coefficient of the reflector, particularly in the portions of the reflector closest to the reactor core. It is therefore essential

that neutron absorption in the reflector be reduced to the lowest possible level. This is accomplished by controlling the impurities in the beryllium carefully and by providing the minimum practical cooling water content in the reflector.

Corrosion

As in most aqueous corrosion problems, the aqueous corrosion of beryllium is extremely complex. Water is a good electrolyte, and the corrosion of beryllium is largely electrolytic in nature. Impurities or inhomogeneities in the water or in the beryllium can have a marked effect on the corrosion rate. Contact of the beryllium with dissimilar metals can also influence the corrosion rate. Mechanical joints of stainless steel to beryllium were observed to result in severe pitting of the beryllium under operating conditions in the HFIR,⁴⁴ and such joints should be avoided.

The types of corrosion attack also vary. Apart from general corrosion over the whole exposed surface, localized corrosion or pitting can occur in areas anodic to the bulk of the material so that the actual penetration may be much greater than indicated by the general rate of corrosion. Since corrosion in water is largely electrolytic in nature, it is best reduced by keeping the water as pure as possible; that is, by keeping the electrical resistance high through the elimination of dissolved impurities. For good corrosion resistance in general, it is also advisable to keep the beryllium as pure as possible.

Beryllium exhibits good corrosion resistance in water at temperatures below 100°C when adequate standards of water and metal purity are maintained. In this respect, carbide and chloride inclusions in the metal and chloride or sulphate ions in the water are particularly deleterious. With the current standards for metal purity, the major factor in the corrosion problem is the purity of the water. In the absence of other corrosive agents, oxygen tends to have a beneficial effect. Corrosion inhibitors are known but are not too effective, and they must be selected to suit the particular environment or their effects may be detrimental

rather than beneficial. In water at elevated temperatures ($> 300^{\circ}\text{C}$), the behavior is less certain and only limited corrosion resistance seems possible. The deleterious effect of minor impurities is emphasized at these elevated temperatures. The use of surface treatments or coatings to increase corrosion resistance is discussed in Chapter 5.

Mechanical Loading

At the present, beryllium components in reactors are not intended to carry any sizable mechanical load because of possible high thermal- and irradiation-induced stresses. When these stresses are fully understood and brought under control, there is no reason that beryllium components cannot carry mechanical loads. However, any possible mechanical load on a beryllium component should be superimposed on the thermal- and irradiation-induced stresses wherever possible.

5. BERYLLIUM FABRICATION METHODS

The application of beryllium depends to a large extent upon its fabricability. The need for rather elaborate production processes and the associated cost required to produce beryllium components of the desired size and shape have attributed to the fact that beryllium has not been used extensively despite the advantages offered by its strength-to-weight and modulus-to-weight ratios and its thermal and nuclear properties. The existing methods by which beryllium components are fabricated include powder fabrication processes and hot forming processes. These and the processes by which beryllium is joined, machined, surface treated or coated, and tested are discussed in this chapter.

Powder Metallurgy

The major portion of the beryllium used in nuclear and space applications is made by using powder fabrication processes,^{2,3,6,11} and a comprehensive review of the powder metallurgy of beryllium has been published by Porembka, Hanes, and Gripshover.⁴⁵ There are several processes by which blanks of beryllium components are made from powder, and the most commonly used of these is hot pressing. Pressureless sintering of beryllium powders has been investigated recently as a means of retaining an isotropic finished material.

Hot Pressing

Hot pressing is the most common powder fabrication method, and most commercial beryllium products are fabricated by pressure compacting the powder at elevated temperatures under vacuum conditions.⁴⁵ This process can be carried out at various combinations of temperature and pressure, ranging from temperatures as low as 500°C at a pressure of 50,000 psi to a temperature of 1100°C at a pressure of 500 psi. These parameters and

the time under pressing determine the density and influence the mechanical properties of the resulting beryllium product.

Under vacuum hot pressing conditions, beryllium powders are densified primarily through plastic flow of the material under pressure. This process is also aided by diffusion, evaporation, and condensation, particularly in the promotion of particle bonding and closure of pores. Vacuum hot-pressed beryllium is practically free of porosity. The relatively short hot-pressing time is favorable for obtaining a desirable fine-grained structure, as distinguished from vacuum cast material characterized by large-grained structures. As previously discussed, the mechanical properties, especially the strength, of the beryllium product depend upon the grain size and the BeO content. The density of vacuum hot-pressed beryllium is usually higher than 99.5% of the theoretical value, and the grain structure is also randomly oriented to give a more or less isotropic material. The use of fine powders can improve the strength, stability, and other properties of the material.

Beryllium produced by the vacuum hot-pressing process has excellent machinability, and it can readily be rolled, forged, and extruded by using standard techniques developed for beryllium. Large-size products can be made by the vacuum hot-pressing process. It should be mentioned that the common powder fabrication process of pressure compacting powders at room temperature and subsequent sintering is hardly applicable to beryllium powders.

Pressureless Sintering

Pressureless sintering of beryllium powders is a recently developed process not yet adapted for production purposes. Loose powders or vibratory-compacted powders can be sintered up to very high densities if the size and distribution of the powder particles are carefully selected and controlled. Pressureless sintering has many interesting aspects. In pressure compacting and subsequent sintering, the powder particles are somewhat deformed and therefore oriented, and the deformation of powder particles also usually results in some orientation of voids or pores

between the particles. The grain structure of a unidirectionally pressed mass of powder is therefore not isotropic. Beryllium powder-fabricated parts prepared by pressureless sintering do not exhibit orientation effects. The loading of powders prior to sintering is done either by tamping or vibrating to packed densities of between 45 and 50% of the theoretical density, and this does not result in deformation of the particles or orientation of voids. During the subsequent sintering, the powder mass shrinks uniformly from all directions, resulting in a uniformly grained structure.

Pressureless sintering of beryllium powders was initially investigated by Barrett, Ellis, and Knight⁴⁶ with a minus 200-mesh powder produced from electrolytic flake beryllium. Careful attention was paid to the particle size distribution of the powder, which was placed in a graphite mold that was induction heated under vacuum conditions for the sintering process. Despite high linear shrinkage, good shape retention of the compact was retained. The density achieved by pressureless sintering is affected by time, temperature, and the purity of the powder, and high densities can be achieved only at temperatures of 1175°C and above. Pressureless sintered beryllium with a density of 98% is not permeable to gases at high temperatures, and the tensile properties of the sintered metal are isotropic and improve with increasing density.

Hot Forming Processes

In order to use beryllium more efficiently and enhance its mechanical properties, several hot forming processes have been developed.^{2,3,11} These include hot forging, rolling, and extruding.

Forging

In the hot-forging process, beryllium block material is placed in a mild-steel jacket, heated to a temperature of 1950°F, and hot forged. This process increases the strength and ductility of the material and

reduces the machining required when block material is used. The increase in strength depends upon the severity of the work, but an increase of at least 10% over the original properties of the block can be expected. Forgings are especially useful for large simple shapes, but they are not recommended for complex shapes with sharp corners.

Sheet Metal Fabrication

Two principal methods are used to manufacture beryllium sheet and plate material, and these are hot upsetting and cross rolling. The hot-upset sheet is essentially forged material. Cross-rolled sheet is produced by cross rolling a mild-steel jacketed billet at elevated temperatures ranging from 800 to 2000°F. Although it does not have a consistent effect on the mechanical properties of the rolled material, an annealing cycle is recommended to promote better formability. Experimental rolling of billets without cladding has been done at lower temperatures (850 to 1100°F) to produce thin foils of beryllium for physical experiments.

Techniques for the forming of beryllium sheet are not very highly developed, but sheet, plate, and strip material are generally hot formed at temperatures ranging from 800 to 1400°F, preferably in the upper portion of the range. Sheet and plate material between 0.005 and 0.500 in. thick have been shaped, bent, spun, deep drawn, shear formed, stamped, and cupped, using both reduction and bending techniques. Temperatures up to 1400°F may be used for thicker sections and heavier bends. Shearing should be performed at temperatures above 1000°F, and the temperature should be increased as the thickness of the material is increased. The deep drawing properties of beryllium at high temperatures are similar to those of carbon steel at room temperature except that the total elongation of beryllium is from one-third to one-half that of carbon steel. In addition to temperature, the rate of forming required to produce desirable reductions or bend radii, tool design, material chemistry, and the effect of the surface condition are also important factors.

Extrusion

When compared with the conventional methods used for aluminum and steel extrusions, the extrusion techniques that must be used for beryllium are rather sophisticated. The primary reason that beryllium is difficult to extrude is its tendency to gall and stick to the extrusion tooling, and once this action has started, the beryllium will wash the die away by abrasion. Turbulent beryllium flow will therefore produce a catastrophic die wear condition. Another problem involves uneven metal flow between the center and the surface of the billet that is caused by friction and chilling when the hot beryllium contacts the extrusion tooling. This can cause cracking or scaling and a lack of reproducibility.

The conventional method used to extrude beryllium has been to extrude a steel-jacketed billet, and the usual forms of extrusions have been rounds, squares, and rectangles. The jacket prevents oxidation, minimizes toxicity, and protects the tooling. Copper plating has also been used on jackets, and special lubricants containing mica or asbestos have been used to reduce the surface chilling and friction.

Attempts have been made to develop a bare extrusion process whereby complex beryllium shapes can be generated to close tolerances. Some of the conclusions produced by the effort are that a higher ram speed gives more consistent results, reproducibility has been established, a billet temperature of 1750°F yields good extrusions, and there is possibly a narrow lubrication tolerance. Ultimate strengths of 90 ksi in tension are attained on extrusions, but because of the highly preferred orientation, extrusions are brittle in the transverse direction. Therefore, only axial loadings are recommended for beryllium extrusions.

Joining Methods

Maximum engineering utilization of fabricated beryllium requires the use of both mechanical and metallurgical joining processes to obtain the

desired components with high strength-to-weight ratios. Most of the common manufacturing joining methods and some newly developed ones have been applied to some degree to beryllium.^{2,3,6,11}

Mechanical Fasteners

Such mechanical fasteners as screws, studs, and rivets have been used to join beryllium to beryllium or to other metals. Special care must be exercised in locating and preparing the holes for fasteners, and fasteners are not recommended for complicated shapes because the high elastic modulus of beryllium produces sharp stress concentrations around them. Mechanical fasteners can be used in conjunction with bonding by resins, solders, and braze materials to provide attachment studs or to fix a joint in position for additional strength or restraint against movement.

In evaluating test specimens joined with mechanical fasteners, some trends are noteworthy. Bending stresses exist in the overlap joints of riveted or bolted beryllium sheet assemblies. Test specimens often fail at the fastener under normal tensile stresses of 20 to 30 ksi instead of the 70-ksi value for the beryllium sheet before joining. For beryllium sheet and block joined by screws and bolts, the thinner specimens fail by sheet tension and the thickest (0.375 in.) usually fail by fastener shear at room temperature. In a temperature range from 500 to 1000°F, the thin and intermediate-thickness specimens fail through joint deformation and the thickest fail by fastener shear. From room temperature through 1200°F, reductions in joint strength with increasing temperature are mainly caused by a loss of fastener strength; and at temperatures over 1200°F, the primary cause of joint strength reduction is loss of strength of the beryllium. The effective strength of the beryllium is increased from room temperature to 500°F because of the decreasing notch sensitivity.

Adhesive Bonding

Adhesive bonding might be a useful method of joining beryllium in many applications. This method of joining would eliminate the notch

sensitivity problem present when an attachment pattern is drilled in beryllium sheet. Synthetic resins can be used for beryllium bonding at relatively low shear strengths (about 5000 psi at room temperature) and at low temperatures (less than 300°F). The lower temperature range where adhesives are most effective is also the range where normal mechanical joining methods are the least effective.

Welding

Reviews of the literature related to the various methods of metallurgical joining of beryllium indicate that some methods are well established while others have progressed only to a definition of the problem areas.

Resistance welding seems to offer little promise as a means of joining because of the notch sensitivity of beryllium and the cracking of welds. Although feasible, spot welding has not been used much, nor has flash welding because of the necessity of preventing the release of beryllium dust into the surrounding air.

Diffusion welding depends upon the use of heat and pressure to form atomic bonds. Beryllium joints have been produced under conditions of hot pressing, but they are not reliable in many cases because the layers of beryllium oxide on the mating surfaces prevent cohesion.

The inert-gas shielded-arc method of fusion welding beryllium with arc atmospheres of argon or helium has not generally been too satisfactory. The problem areas involved in fusion welding of beryllium are hot tearing, grain growth, and porosity. The major problem involved in the use of the inert-gas shielded-arc method is one of maintaining thermal equilibrium in the work to prevent cracking and distortion. One solution is to use low-energy inputs and a slow welding rate. Another solution that is not desirable for large or complicated structures is to preheat the beryllium. The mechanical properties of the weldments depend upon the grain size in the weld metal; the finer grained develop better properties at room temperature and the coarser grained show a better advantage at temperatures above 1100°F. For optimum room-temperature properties, the largest grains

in the weld metal should have diameters no larger than 30 microns. A weld metal with grains whose diameters are over 100 microns is considered unsuitable for most applications. Generally, this type of beryllium fusion welding should be considered only for low-stress applications at temperatures exceeding 1000°F where pressure welding cannot be used. Argon shielding gas and a dry box are recommended to minimize oxidation.

The electron beam method of fusion welding has been used for precise localized joining of beryllium, taking advantage of narrow heat-affected zones, low distortion, and the ability to operate under vacuum conditions. Because of the high vapor pressure of beryllium at temperatures close to the melting point, the concentration of heat by the electron beam has been reported to produce rather severe porosity in the bead and full advantage of the heat concentration cannot be realized. This is especially true in view of the high thermal conductivity of beryllium.

Pressure welding in a vacuum is a recommended beryllium joining method for all applications where proper jigging can be used. No filler metals are required, and this prevents the formation of brittle inter-metallic compounds from the beryllium and the filler metal. The reduced joint efficiencies that normally occur at elevated temperatures when fillers with lower melting temperatures are used are avoided. Optimum pressure welding yields joint efficiencies of 100% with no degradation of the ductility or high-temperature properties of the parent metals. An evaluation of pressure-welded joints in hot-pressed beryllium block material showed that weld strengths increase with higher welding temperatures, reach a maximum, and then decrease because of grain growth. At lower welding temperatures, weld strengths are much better when the surfaces are smooth, but surface roughness does not appear to be significant at welding temperatures above 1920°F.

In the ultrasonic or cold welding process, thin sheets of beryllium are joined under moderate static force with superimposed vibratory energy introduced for a short time through a welding tip. Beryllium foil has been joined to itself or to other metal foil at room temperature by using this process, which is usually applied to materials no thicker than 0.020 in. Shear strengths in beryllium of up to 18,000 psi have been obtained, and the process appears to offer promise for special applications.

Soldering and Brazing

With the proper selection of flux and solder material, beryllium has been soldered for relatively low-strength joints. Soft solder is effective when a press-fit joint is used, and a Pb-Sn-Zn solder on silver-flame-sprayed beryllium develops good strength.

Brazing is the metallurgical joining method most frequently used when high joint strength and temperature resistance are desired. Brazing gives reliable results with a minimum of porosity, brittleness, and notch buildup. Beryllium can be brazed to beryllium or to other metals such as nickel, stainless steel, and copper. The proper selection of the brazing alloy depends upon the application of the finished product and the metals to be joined. Silver, aluminum, silver-copper, and aluminum-silver alloys have been used at room temperature; but silver seems to be superior for elevated temperature applications. Aluminum is used for nuclear applications and under conditions where a weaker filler metal with a lower melting point is desired, and silver is used primarily to meet higher strength and elevated temperature requirements. Ultimate tensile strengths of 40,000 psi can be developed with pure silver.

Preplacing the braze material and/or the addition of 0.2% lithium is the preferred practice because of the low wettability of beryllium. The oxidation problem is met by brazing in an inert atmosphere or in a vacuum. When beryllium is being brazed to another metal, the assembly should be held at the braze temperature for as short a time as possible to avoid the development of intermetallic brittleness that occurs between beryllium and nearly every other metal except silver.

Machining Methods

The increased use of beryllium in recent years in aerospace and atomic energy applications has led to the accumulation of considerable experience in the machining of beryllium.^{2,11} The machinability of beryllium is comparable with that of cast iron even though beryllium

is more brittle and abrasive. However, its rigidity and dimensional stability permit minute machining operations of beryllium with the attainment of close tolerance.

Nearly all types of machining operations have been performed on beryllium. The standard lathe operations of turning, threading, and boring are readily performed on beryllium, and milling of beryllium is quite similar to the turning operations. Drilling is one of the more difficult operations performed on beryllium, but it does not present insurmountable problems when care is exercised and the proper procedures are followed. Grinding of beryllium is a machining operation used less frequently than others because finishing cuts made by other machines usually cannot be improved if the tools are in good condition. Billets of beryllium are usually parted or subdivided by using a handsaw. Detailed recommendations for the proper performance of these operations are given by Crawford and Burns.¹¹

In general, carbide tools are preferred for turning, milling, and drilling operations, and it is important that the cutting edges be kept extremely sharp. Those part sections vulnerable to distortion and vibration during machining should be supported rigidly, and back-up fixtures, dampening mandrels, or other such devices to counteract tool pressure deflection should be used to assure machining accuracy. Heavy-duty equipment with enough power reserve and a minimum of transmission backlash to permit no-chatter machining at the desired speed, feed, and cutting depth should be used. Because beryllium metal and its compounds are potentially toxic, positive action must be taken to prevent the dispersion of beryllium particles in working areas. This can be done by performing machining operations under high-speed air exhaust equipment or by using a coolant or water-soluble lubricant inert to beryllium to suppress dust particles, cool the work, and to wash away chips. Cutting fluids should not be reused for machining non-beryllium parts, and wet chips and turnings should not be intermixed with clean dry chips and turnings.

Surface Treatment and Coating

Surface treatment is probably the least developed area of beryllium technology, and a great deal of research is needed in this area before a state of the art comparable with that of the more common structural metals can be achieved.^{2,3} The major portion of beryllium components are placed in service with as-machined surfaces. However, work is presently being done on surface treatments and coatings for beryllium primarily to improve its corrosion resistance, mechanical properties, and wear resistance, and to facilitate joining operations such as brazing.

The as-machined surfaces of beryllium are normally covered with a nonporous protective oxide film about $100 \overset{\text{O}}{\text{\AA}}$ thick. This limiting thickness is reached after two hours of exposure to the atmosphere at room temperature. The BeO formed occupies about 1.68 times the volume of the metal, and it therefore produces a state of compressive residual stress on the surface. This layer of oxide must be removed before other materials can be bonded to or plated on the beryllium surface. Another characteristic of machined beryllium surfaces is that they may contain twinned areas and microcracks of varying depth, and both affect the mechanical properties of the component.

The machining of intricate surfaces by using etching solutions and suitable masking is gaining popularity, and pickling or chemical polishing has been used to clean oxide from as-machined surfaces of beryllium. One principal disadvantage of the chemical polish treatment is that an orange-peel type of texture quite frequently develops on the beryllium. The resulting surface is semipassive and not suitable for further treatment such as electroplating, anodizing, and bonding.

Electroplating has been used to improve corrosion and wear resistance of beryllium surfaces and to facilitate brazing and soldering operations. The main problem in electroplating beryllium is one of removing the adherent oxide film and obtaining a chemically active surface without preferentially attacking the metal and creating pits. This problem has not been solved completely. The beryllium surface to be plated is usually a machined one, and gross scale and impurity removal is not a problem.

When a non-machined surface is to be plated, the HF-nitric etching process has been satisfactory in removing scales prior to other surface treatment before plating.

Anodizing is widely used for magnesium and aluminum surfaces, and it is also becoming an important finishing treatment for beryllium. This type of surface treatment is used primarily for corrosion resistance at the present. As previously discussed, the general corrosion resistance of beryllium in low-temperature high-purity water is quite good, but its behavior in high-temperature (500 to 650°F) water is erratic. This characteristic has precluded the use of beryllium in high-temperature water and steam applications. Beryllium is also susceptible to a pitting type of corrosion when exposed to water containing even small amounts of chloride ions, and it is also known to corrode in dry and wet CO₂ atmospheres. Anodizing has been used to protect beryllium surfaces from corrosion by oxidation and by CO₂ at temperatures up to 1290°F. The anodized film will also protect beryllium from corrosion in low-temperature deionized water and even tap water, and good protective results were also obtained in the ASTM salt-spray tests. Of the surface treatments available for beryllium at the present, anodizing is the most highly recommended for increasing the overall corrosion resistance of the base metal. Anodizing of beryllium may also be developed in the future to provide a wear-resistant surface for controlling emissivity and for improving the appearance where desirable.

Another type of protection for beryllium surfaces is offered by spray coatings. The surfaces to be coated are first treated by sand blasting or other similar techniques, etching in a dilute acid, and by cleaning with organic solvents prior to the spraying operation. Coatings that have been applied to beryllium by spraying include tungsten, carbide, aluminum oxide, and chromium oxide.

Nondestructive Testing

All of the currently practical methods of nondestructive testing⁴⁷ may be used for beryllium, but the two main methods in use are liquid

penetrant for surface discontinuities and radiography for internal integrity.⁴⁸ Eddy current testing is sometimes used to locate surface and subcutaneous defects. Ultrasonic techniques, including through transmission and back reflection, can also be used to locate defects, but these methods have been relegated to a supporting role except in those cases where neither the liquid penetrant nor the radiography methods can be used successfully.

Liquid Penetrant Testing

Liquid penetrant testing of beryllium is accomplished by the same methods normally used for other materials, and the types of surface discontinuities that may be detected range from cracks to minute exposed inclusions and porous or low density areas. If machining or heavy milling operations smear the surface of the beryllium to the extent that the penetrant cannot penetrate the defects, the smeared surface is usually treated by chemical etching before testing.

Radiographic Testing

Radiographic testing is by far the most accurate gauge of the internal integrity of beryllium. However, the low density of beryllium and its transparency to X-rays make the use of special radiographic techniques necessary to identify nonmetallic inclusions, striations or variable density areas, discontinuities, and voids in fine-grained beryllium. The X-ray absorption coefficient of beryllium is the lowest of all the elements except hydrogen, and radiographic film contrast is more difficult to obtain for beryllium than for nearly all other materials. Conversely, the presence of small particles of nearly any other element or material in beryllium will appear as high-density (low film density) indications.

The type of equipment generally used has a low voltage, small focal spot, and tubes with very low filtration. Beryllium itself is ideally suited for use as the window material in X-ray tubes because of its high permeability to X-rays (approximately 17 times greater than that of

aluminum), strength, and high melting point. Tubes with beryllium exposure windows have made the use of longer wave X-rays possible in such applications as X-ray therapy and the X-ray study of light metals.⁴⁹ This type of equipment is normally operated in the 20 to 45 kv range. The choice of film holders is also critical, and the most suitable films are fine-grain high-contrast films packaged in disposable paper holders. Another extremely important factor is the cleanliness of the surface of the part being tested and of the film holder.

In radiographic testing of heavy sections of beryllium, scattered radiation degrades radiography quality and film contrast is poor. A technique heretofore used only in medical radiography has been applied to heavy section radiography of beryllium in recent years to alleviate this situation.⁴⁸ A Potter-Bucky reciprocating lead grid is placed between the part being tested and the film during the exposure of heavy sections (3, 8, or 12 in.), and this greatly reduces the amount of radiation scattered within the beryllium that reaches the film. Only that radiation which has penetrated normally through the part reaches the film.

At present, the internal quality of beryllium is determined by using a rather tedious procedure. Films are rated by measuring a film area equivalent to 1 in.³ of the part being tested, counting and measuring the number and size of all the inclusions in this area, and factoring these values by assuming that each inclusion is a sphere. The total volume of all the inclusions in the cubic inch becomes the index of the material quality. There are four main grades in use today. The highest grade is that whose total inclusion volume content per cubic inch does not exceed that of a 0.015-in.-diameter sphere (volume = 1.8×10^{-6} in.³). Other grades are based on total inclusion volumes not in excess of that of a 0.020-in.-diameter sphere ($.2 \times 10^{-6}$ in.³), a 0.032-in.-diameter sphere (17×10^{-6} in.³), and a 0.050-in.-diameter sphere (66×10^{-6} in.³). The last is the most common.

Ultrasonic Testing

Thus far, the use of ultrasonic techniques to test nuclear reactor components has had rather limited application.⁵⁰ Ultrasonic testing of beryllium is not used to any great degree mainly because of the difficulty involved in interpreting accurately the indications seen in the cathode ray oscilloscope presentation. The ultrasound passing through beryllium is reflected by numerous conditions, and a great many of these conditions are in themselves not necessarily deleterious to the material. Variable density areas may be so oriented to give an ultrasonic indication because of slight changes in ultrasound velocity, but these areas may be barely perceptible and fully acceptable by radiographic inspection. On the other hand, the orientation of large inclusions may be such that they are completely missed by ultrasonic inspection.

Ultrasonic testing seems best suited to in-process inspection of large blocks whose thickness rules out the use of radiography. Ultrasonics would then be the only available means of nondestructive testing by which gross internal defects could be detected and the depth of obvious surface defects could be traced. Any requirement for final inspection by ultrasonic testing should be linked with radiographic testing, and the requirements for radiographic testing should provide the ultimate criteria for acceptability.

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