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Beryllium-Aluminum Alloys

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A new series of ductile Be-Al alloys are described which have the advantages of Be, viz., high modulus and low density, but without many of the disadvantages of unalloyed Be. Mechanical properties of the alloys can be varied considerably (tensile strength from 43 to 88 ksi, Young's modulus from 24×10, to 37×10^6 psi), making a wide range of tradeoffs possible, not only between ductility and strength, but also between ductility and modulus. Ductility improvements (relative to Be) are demonstrated by large increases in bend angles in sheet, as well as bends in *T* sections. Comparisons on bolted joints and test welds are also given. Structural optimization data for integrally-stiffened wide columns show that Be-Al offers weight savings of approximately 40% over currently used Mg alloys. With respect to secondary neutron production in Be by space protons, a preliminary study indicates that only with low-energy protons is the effect enhanced in Be in comparison with Al and other elements, but that it will not under any circumstances constitute a health hazard.

Nomenclature

E = Young's modulus in compression, psi
E_t = tangent modulus in compression, psi
k = coefficient for the local buckling mode
k_s = shape factor
L = column length, in.
n = exponent in the Ramberg-Osgood equation
q = axial compression load, lb/in.
q/L = structural index, psi
t = effective thickness, in.
W = weight, lb
W_i = weight of column per unit width, lb/in.; W_i/L^2 is unit weight parameter, lb/in.^{3}
η = plasticity correction factor
ρ = density, lb/in.^{3}
ρ^* = radius of gyration, in.
σ = stress, psi
σ_{cr} = critical buckling stress, psi
σ_{cy} = compressive yield stress, psi
σ_0 = $\frac{7}{10}$ secant yield stress, psi
σ_{opt} = optimum (minimum weight) stress, psi
σ_{tu} = tensile ultimate stress, psi
σ_{ty} = tensile yield stress, psi

Subscripts[¶]

Be = beryllium
x = material x

Introduction

IMPROVED weight-carrying capability in missiles and space vehicles can be accomplished by reducing inert weight, thus permitting greater payloads, more experiments per mission, more alternative missions per vehicle-booster, and/or greater useful orbit lifetime. Inert weight can be reduced in five ways: 1) increased reliability and thereby reduced redundancy, 2) more compact electronic systems, 3) complete system simplification and redesign, 4) improved propellants, and 5) better structural materials. The efforts already expended on reliability leave only about 1% in weight savings as a goal that might be achieved by increased reliability in electronics and 1% in other fields. In electronic systems, high-density packaging might permit a 2% reduction and microminiaturization another 5 to 10%. Complete system simplification and redesign could conceivably result in a reduction of 18 to 25%, but high cost would probably make this course impractical. Development of exotic propellants offers large equivalent weight reductions (50 to 100%), but this course is also an extremely expensive one. The development of new or improved low-density structural materials offers an estimated maximum weight savings of 25 to 35%; this is likely to be the area of greatest development-cost effectiveness. However, comparatively little effort or money has been spent in this field in recent years. Consequently, the present study was aimed at providing a new and useful light alloy for aerospace vehicles.

When one examines the light metals or alloys as structural materials, one is limited to Mg, Al, Ti, and their alloys, or Be. Theoretically, Be should be an exceptionally good material to use in aerospace vehicles because of the high structural efficiency that one would expect when subjecting it to compression loading. However, certain undesirable characteristics of Be, viz., brittleness, low bend ductility, sensitivity to surface damage and defects, chemical etching requirements following working, poor weldability, and fabricability have led to poor structural reliability, and high manufacturing costs and have severely curtailed its use.

It was apparent that an alloy was needed which would closely approach the desirable characteristics of Be (high Young's modulus and low density) but alleviate or eliminate the undesirable ones by using as the second component a very ductile material. Face-centered cubic Al was selected as the soft ductile envelope material for the hard Be particles, because good plasticity results from the multiple-slip systems of Al, and it has a relatively low density.

Although several investigators (Johnson,[1] Sawyer and Kjellgren,[2] Sawyer,[3] and Klein et al.[4]) have studied the Be-Al system, some as early as 1938, the low ductility obtained prevented Be-Al alloys from gaining commercial significance. Despite the discouraging results encountered by these investigators, it was decided that large weight savings that would result from a successful development of commercially useful Be-Al alloys warranted the financial risk of reinvestigating this system.

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[¶] See also dimensions shown in Figs. 10 and 11.

Table 1 Material property and weight index comparison of Be-Al extrusions and sheet at 75°F

Material[a]	σ_{cy}, 10^3 psi	σ_{ty}, 10^3 psi	σ_{tu}, 10^3 psi	Elongation, %	E, 10^6 psi	Density, lb/in.^{3}	W_e, Eq. (1)	W_p, Eq. (2)
Beryllium (*S*)	58	58	86	21	42	0.066	1.0	1.0
Be-24% Al, (*E*)	...	72	88	3	37	9.072	1.16	..
Be-31% Al, (*E*)	...	78	83	2	34	0.074	1.24	...
Be-33% Al, (*E*)	...	76	82	4	34	0.074	1.34	...
Be-36% Al, (*E*)	71	75	76	1.2	32	0.075	1.48	0.92
Be-43% Al, (*E*)	59	63	69	1.5	29	0.077	1.51	1.14
Be-33% Al, (*EA*)	...	43	61	9	29	0.074	1.34	...
Be-36% Al, (*EA*)	39	43	53	9	28	0.075	1.38	1.68
Be-43% Al, (*EA*)	30	36	43	9	25	0.077	1.51	2.25
Be-31% Al, (*S*)	...	67	79	5	30	0.054	1.32	...
Be-36% Al, (*S*)	...	60	70	8	27	0.077	1.41	...
Be-43% Al, (*S*)	...	55	64	12	26	0.077	1.48	...
Mg HM21A-T81, (*S*)	26	30	75	6	6.5	0.064	2.49	2.18
LA141, (*S*)	18	18	22	19	6.5	0.049	1.88	2.39
Al 2024-T3, (*S*)	...	44	61	20	10.6	0.100	3.01	1.99
X2020-T6, (*S*)	81	...	...	7	11.4	0.098	2.85	1.06

[a] (*S*) = sheet, as rolled; (*E*) = extruded; (*EA*) = extruded and annealed.

Discussion and Results

The Be-Al phase diagram indicates that the solid solubilities of Al and Be in each other are limited but sufficient to give more than a mechanical contact at the interphase boundaries. Evidence[5,6] shows that greater ductility results in metallic composites when the hardness differential between the soft and hard phases is decreased. In this case, the hardness differential can be diminished by preferential solute hardening of the soft phase. The soft phase is believed to take the major part of the initial plastic deformation, thus protecting the hard phase from stress concentrations that would lead to early fracture. The envelope of soft Al also supports (hydrostatically) the deformation of the essentially single-phase Be particles, thereby permitting basal slip to occur to a greater extent than is normally possible in Be grains, for example, when QMV beryllium is deformed. In the latter material, the constraints and stress concentrations quickly create cracks, and fracture soon follows.

In the research program, Be-Al sheet and extrusions containing 24 to 43 Al** were produced. These alloys have significantly improved ductility as compared to Be. Metallurgical control of this system has been achieved, so that a wide range of properties can be attained (Table 1). Although the Be-Al properties described herein for developmental extrusions and sheet do not necessarily represent those that may be obtained in commercial production, any changes that may occur in production should not alter the relative rankings shown in the subsequent structural considerations.

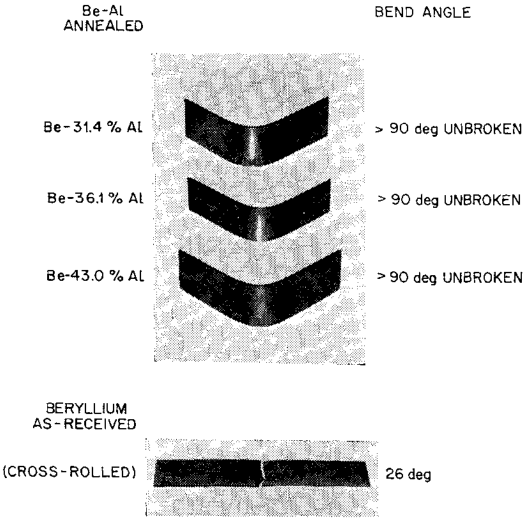

Fig. 1. Bend angle comparison between Be-Al alloys and Be.

Mechanical Properties

Extrusions

The wide variation of Young's modulus (25×10^6 to 37×10^6 psi) achieved with extrusions (Table 1) shows the considerable control over elastic strength which can be attained by proper metallurgical control. Both elastic modulus and strength decrease with annealing and increased Al content (Table 1), whereas the ductility as measured by bend angle increases (Table 2). Although this behavior would be expected of the strength and ductility, the 5×10^6 psi change in modulus upon annealing is certainly unusual, and such a large effect is not seen in most alloy systems. Compression yield strengths are approximately 4 ksi lower than the tensile yield strengths.

The superior ductility of Be-Al extrusions over Be is illustrated by the bend angle data in Table 2. Annealing these extruded Be-Al alloys makes them six to ten times as ductile as the commercially pure Be. Comparison of Be-Al to Be in a nonstandard impact test (specimen 0.1 by 0.5 in.) showed some extruded Be-Al to have a strength of 68 in.-lb whereas the Be had only 9 in.-lb. [Elongation figures are given in Table 1 as a matter of information, but the authors do not consider uniaxial elongation in either Be or Be-Al alloys to be an adequate evaluation of ductility, because the material may respond differently under complex stressing. For ex-

Table 2 Bend angles[a] of 0.058-in.-thick Be-Al extrusions at 75°F

	Bend angle, deg		
% Al	w = 1.25 in.	w = 0.50 in.	w = 0.25 in.
33	8	14	33
33[b]	51	73	76
36	15	12	5
36[b]	50	59	76
43	17	17	27
43[b]	56	65	81
Be	7	9	8

[a] Three-point loading: span = 1.5 in.; mandrel radius $\frac{1}{32}$ in.
[b] Annealed; w = specimen width.

** Numbers used throughout in connection with alloy composition represent weight percent.

Table 3 Mechanical properties of Be-Al sheet at 75°F

		Longitudinal properties					Transverse properties				
Alloy, % Al	Rolling direction[a]	E, 10^6 psi	σ_{ty}, ksi	σ_{tu}, ksi	Elong., %	Bend[b] angle, deg	E, 10^6 psi	σ_{ty}, ksi	σ_{tu}, ksi	Elong., %	Bend[b] angle, deg
31	Long.	30.4	67	79	4.6	67	...	...	. .	...	...
31[c]	Long.	29.8	41	61	6.5	>90	...	. .	...	...	...
36	Long.	27.3	60	70	8	81	...	...	...	...	...
36	Bidir.	28.4	45	56?	5?	...	26.4	39	44	1	...
36[c]	Long.	27.9	37	55	8	>90	...	...	...	...	...
36[c]	Bidir.	28.6	40	52	4	...	26.9	36	45	2.5	...
43	Long.	25.8	55	64	12	85	...	...	...	...	54
43	Bidir.	24.2	37	44	4?	...	27.2	36	48	8	...
43[c]	Long.	24.6	33	50	13	>90	...	...	...	...	108
43[c]	Bidir.	...	. .	...	...	...	23.4	26	39	9	...
Be	Bidir.	42	53	74	9	26	...	...	...	...	...

[a] Long. = longitudinal; Bidir. = Bidirectional (longitudinal plus cross-rolling).

[b] Thickness =0.020 in., width = 0.5 in.; three-point loading: span = 1.5 in., mandrel radius = $\frac{1}{32}$ in.

[c] Annealed.

ample, cross-rolled Be sheet with an elongation of 2 to 6% has a bend angle of 11°, but similar specimens ($W/t = 9$) with 13 and 24% elongation also have bend angles of only 10° to 11°.]

Sheet

The longitudinal and transverse tensile properties and bend angles for various Be-Al sheets rolled longitudinally and bidirectionally are shown in Table 3. The elastic modulus (as-rolled) sheet is approximately equivalent to that of annealed extrusions, and in contrast to the extrusions shows only about a 1×10^6 psi drop upon annealing. Comparison to Be data again shows the alloys to have superior ductility and comparable strength under certain processing conditions but lower elastic moduli. A photographic comparison between 0.020-in.-thick Be-Al and Be bend specimens (Fig. 1) illustrates the relative behavior of these metals under free bend conditions.

Thermal Properties

Values of specific heat, thermal conductivity solar absorptance, and normal emittance for three Be-Al alloys are given in Table 4. The effect of temperature on the coefficient of linear thermal expansion for 33, 36, and 42 Al alloys is shown in Fig. 2. Values of specific heat and thermal conductivity for Be-(32-43) Al alloys are compared to those of Be and HM-21 Mg as a function of temperature in Fig. 3.

Shop and Service Characteristics

A limited number of preliminary tests were made to evaluate the shop and service characteristics of Be-Al alloys. These tests were extremely encouraging and showed several desirable characteristics of Be-Al over Be. A considerable amount of machining (milling and drilling) was successfully and easily performed with conventional high-carbon steel cutting tools. In view of the cracking problems that occur on punching holes in Be, conventional punching operations were performed on Be-(27-43)Al, and the edges of the holes were then studied metallographically for cracks. The Be-Al sheet showed no evidence of cracking or spalling upon punching $\frac{3}{16}$-in.-diam holes in 0.050-in.-thick sheets (see Fig. 4), but instead showed a very fine burr on the exit side of the sheet, demonstrating the adaptability of these alloys to punching operations. This punching operation was used to make some bolted joints between 0.050-in.-thick Be-31.4 Al sheet and 0.100 Mg (see Fig. 5), which gave tensile strengths ranging from 35 to 48 ksi. The maximum strength obtained in equivalent tests of 0.050-in. Be joined to 0.100-in. Mg was 35 ksi.

Table 4 Thermal properties of Be-Al alloys at 75°F

Alloy, % Al	Spec. heat, cal/g-°C	Thermal cond., cal/cm-sec-°C	Thermal diffus., cm²/sec	Solar absorptance[a]
33	0.40	0.46	0.56	0.67
36	0.395	0.51	0.63	0.72
43	0.37	0.455	0.58	0.74

[a] Values vary with surface finish and heat treatment and may be as low as 0.43; all have a normal emittance of 0.09–0.04, depending on surface finish.

Although 90° bends have been made successfully at room temperature on 0.050-in.-thick Be-43 Al sheet, the high Be content of the Be-Al alloys will probably dictate that severe forming operations be performed at elevated temperatures. For this reason, some forming experiments were conducted at 800°F (a substantially lower temperature than the 1300°F required for Be). The results of a 170° bend made on 0.043-in.-thick Be-33 Al sheet is demonstrated in Fig. 6. Lower bend radii were not tried. A *T*-shaped extrusion of Be-41.7 Al was joggled $\frac{3}{16}$-in. and formed to a smooth 29.9-in. radius (Figs. 7 and 8, respectively).

In view of the fact that Be-Al alloys have a eutectic temperature of 1193°F above which they will melt, processing temperatures will necessarily be below this temperature. This means that manufacturing facilities equipped to heat-treat conventional Al alloys would be able to process Be-Al alloys, whereas additional higher-temperature equipment would probably be required to process Be.

A limited number of weld tests were made by the electron beam technique. The Be-Al welds (e.g., Fig. 9) do not show

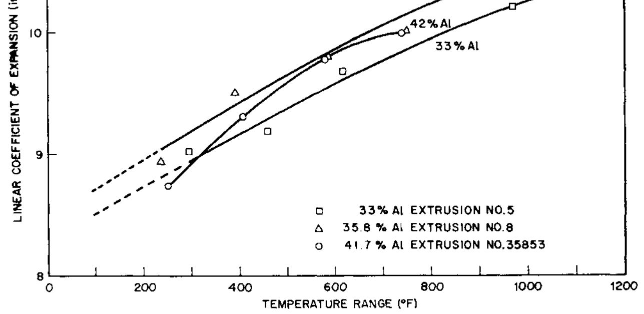

Fig. 2 Linear coefficients of expansion for Be-Al alloys vs terminal temperature.

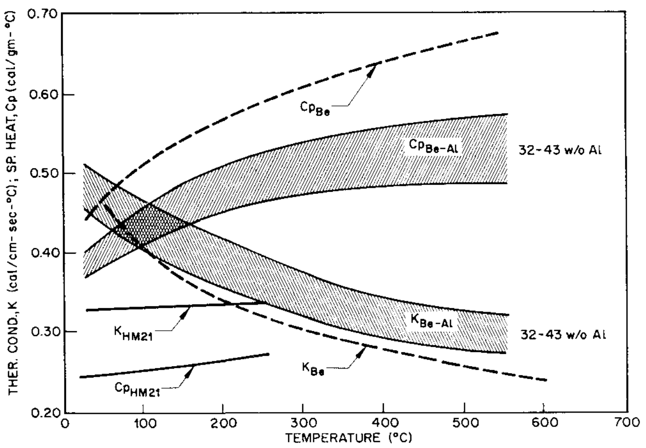

Fig. 3 Thermal property bands for Be-Al alloys compared with Be and HM21.

the susceptibility to cracking which is experienced by Be. Strengths of the flush welds in Be-32 Al in both as-rolled sheet and annealed sheet are approximately the same, 46.6 and 44.7 ksi, giving efficiencies of 56 and 85%, respectively. These strength values are within the strength scatter band for the bolted joints discussed. The corrosion characteristics of these alloys were cursorily examined by exposing specimens to stagnant 3% NaCl for 2 weeks; no visible attack was noted.

In producing all test specimens and panels from Be-Al alloys, no chemical etching techniques or special machining practices were used to remove the "as-processed" surface prior to testing. These alloys are no more sensitive to surface damage or notches than most other common metals. By contrast, the currently available Be must be chemically etched after all working operations to remove damaged surface material.

The use of Be-Al alloys in lieu of Be should lead to significantly reduced manufacturing and installation costs in view of several factors: viz., excellent machinability and punching characteristics; lower forming temperatures; improved joint strengths, forming characteristics, and possible freedom from doubling techniques on joints; weldability; freedom from chemical etching requirements to remove surface damage; and freedom from elaborate shimming techniques.

Structural Considerations

A large fraction of most spacecraft structure is critical under compression loading, which leads to either elastic or plastic modes of failure. The art of minimum-weight analysis is highly developed for simple types of structures,[7] and it is possible, as shown below, to utilize the actual stress-strain diagram to cover the range from lightly loaded to heavily loaded structures. To assess in detail the comparative efficiency of the Be-Al alloys, an analysis such as that given below for an integrally stiffened panel is necessary. However, two very good measures of the structural efficiency in compression are given by the following normalized weight indexes:

$$W_e = W_x/W_{\mathrm{Be}} = \rho_x/\rho_{\mathrm{Be}}(E_{\mathrm{Be}}/E_x)^{1/N} \tag{1}$$

$$W_p = W_x/W_{\mathrm{Be}} = \rho_x/\rho_{\mathrm{Be}}(\sigma_{cy_{\mathrm{Be}}}/\sigma_{cy_x}) \tag{2}$$

The first relative weight index W_e is applicable to structures that fail in an elastic instability mode, whereas the

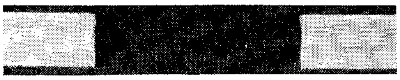

Fig. 4 Macrograph of $\frac{3}{16}$-in. punched hole in Be-26.9% Al alloy.

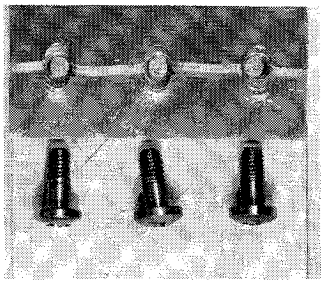

Fig. 5 Bolted joint: Be-31.4% Al alloy to Mg.

second index W_p is applicable to structures that fail in plastic instability mode. The number N is a minimum weight exponent[7] that ranges from 1.67 for trusscore sandwich cylinders to 3 for flat unstiffened panels. On the basis of the preceding relationships, the efficiencies of several materials as well as the new Be-Al alloys are compared to Be. A value of 2 for N has been chosen; this value is applicable to Z-stiffened wide columns.[7] Results given in the last two columns of Table 1 clearly show the superiority of the Be-Al alloys over Mg and Al.

Integrally Stiffened Wide-Column Comparisons

To illustrate the superiority of the Be-Al over the entire load spectrum from lightly loaded to heavily loaded structures, an optimization study was carried out for an integrally stiffened wide column. Four materials, Be-36 Al, Be, HM21A-T8, and 2024-T3 are examined in the following treatment, using properties at 75°F.

The basic principles of optimum design of wide columns were presented by Shanley.[8] The following treatment extends the Shanley approach to the longitudinally integrally stiffened wide column. The method is based on the principle that the optimum column results when it is so proportioned that simultaneous failure occurs in two different modes, column buckling and local plate buckling. Plasticity corrections are introduced to account for stresses above the proportional limit.

The structural index q/L is expressed by[8]

$$q/L = \sigma^{3/2}(\bar{t}/\rho^*)/\pi E_t^{1/2} \tag{3}$$

where

$$\bar{t}/\rho^* = b_s t_s/k_s\, b_w b_s \tag{4}$$

and

$$k_s = m[(1 + 4m)/12]^{1/2}(1 + m)^{-2} \tag{5}$$

and $m = b_s t_s/b_w t_w$ (see also Fig. 10 for notations). Substituting Eq. (4) into Eq. (3), we have

$$q/L = \sigma^{3/2} b_s t_s/\pi E_t^{1/2} k_s b_w b_s \tag{6}$$

Local buckling of the web-stiffened plate is determined from

$$\sigma_{\mathrm{cr}} = k\pi^2\eta E(t_s/b_s)^2/12(1 - \mu^2) \tag{7}$$

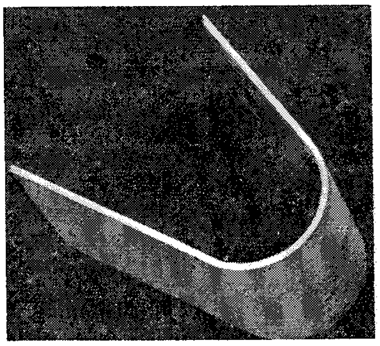

Fig. 6 Bend in 0.043-in. Be-33% Al alloy obtained by hydropress forming at 800°F.

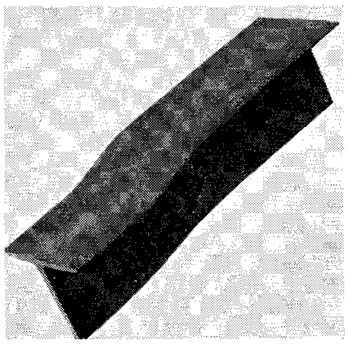

Fig. 7 A $\frac{3}{16}$-in. joggle made at 800°F in Be-41.7% Al extrusion.

Values of k as functions of the ratios t_w/t_s and b_w/b_s are given in Ref. 9 and reproduced in Fig. 11. Solving Eq. (7) for b_s/t_s ($\mu = 0.3$)†† yields

$$b_s/t_s = (0.904\eta kE/\sigma_{\mathrm{cr}})^{1/2}$$

Substituting in Eq. (6) yields

$$(q/L)_{\mathrm{opt}} = 0.335\ \sigma^2/\beta\xi \tag{8}$$

where $\beta \equiv k^{1/2}k_s(b_w/b_s)$ is a shape parameter and $\xi \equiv (\eta E_t E)^{1/2}$ is a material parameter.

The shape parameter is plotted against b_w/b_s for various ratios of t_w/t_s in Fig. 12. The highest stress is achieved when β is a maximum; optimum values of β are noted on Fig. 12. Since the highest value of β occurs when $t_w/t_s = 2.0$, this value will be used in the subsequent investigation. Equation (8) becomes

$$(q/L)_{\mathrm{opt}} = 1.565\ \sigma^2/\xi \tag{9}$$

Weight comparisons for wide columns of various materials are usually expressed in terms of the weight parameter W_i/L^2 where W_i is the column weight per unit width. Thus

$$W_i = w\bar{t}L = \rho qL/\sigma_{\mathrm{opt}} \tag{10}$$

Hence, from Eqs. (9) and (10),

$$W_i/L^2 = \rho(q/L)\sigma_{\mathrm{opt}} = 1.565\,\rho\sigma/\xi \tag{11}$$

Equation (11) was used to establish weight comparisons of wide columns fabricated from Be, Be-Al, 2024-T3 Al alloy, and HM21A-T8 Mg alloy. The values of η, the plasticity correction for local buckling, were taken as $(E_t/E)^{1/2}$, and calculated by means of the Ramberg-Osgood equation

$$(E_t/E)^{1/2} = [1 + \tfrac{3}{7}n(\sigma/\sigma_0)^{n-1}]^{-1/2} \tag{12}$$

The results are shown in Fig. 13, in which curves of a weight parameter W_i/L^2 vs the square root of a loading or structural index q/L are plotted. For a given value of the structural index, the smaller value of the weight parameter means a lighter structure. Values of the structural index q/L for current spacecraft are in the neighborhood of 15 to 20, resulting in $(q/L)^{1/2} \approx 4$. This value is in the left-hand linear region of the curves in Fig. 13. In this region, the slope of the curve on the log-log plot is a function of the material efficiency factor $\rho/E^{1/2}$ and hence represents a domain of elastic instability. The right-hand linear portion is governed by another material efficiency factor ρ/σ_{cy} and hence represents a domain of plastic instability. The knee of each curve is a function of the compressive yield stress; i.e., there is a certain value of the σ_{cy} beyond which further increase in the yield stress will not result in any additional relative efficiency. This means that the developer of the Be-Al alloy need not strive for values of σ_{cy} higher than 45 ksi (the value used in the stress-strain diagram for the preparation of Fig. 13), and instead can concentrate on improving other characteristics, such as the ductility. Such considerations reveal the flexibility available to tailor a material to suit a particular design condition. For example, one can conceive of a Be-Al alloy with a σ_{cy} of only 17,000 psi which is still superior to other alloys for a practically important range of q/L because of its markedly lower ρ and higher E. Since low yield stresses coexist with high ductility, the heat treatment and processing of Be-Al can be directed more advantageously toward the improvement of ductility when necessary.

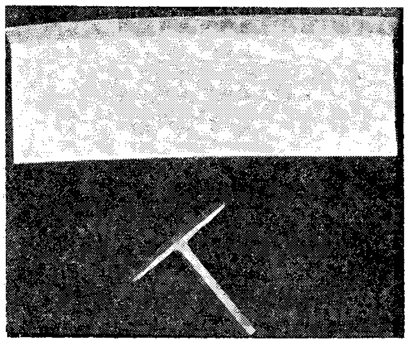

Fig. 8 A 29.9-in. radius made at 800°F in Be-41.7% Al extrusion.

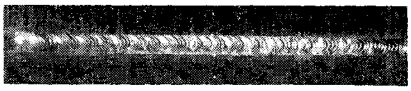

Fig. 9 Electron-beam weld on Be-32% Al sheet.

Effect of Radiation on Be and Be Alloys for Space Flight

Since materials that are used in spacecraft will encounter various types of radiation, one must consider what effect radiation has upon Be and Be-Al alloys from the standpoint of both structural properties and secondary radiation production. Proton radiation in the Van Allen belt and solar flares can induce the important transmutation reaction $Be^9(p, pn)Be^8$, which immediately leads to 2 He atoms. Using 10^{-24} cm^2 as a reaction cross section (conservative to include

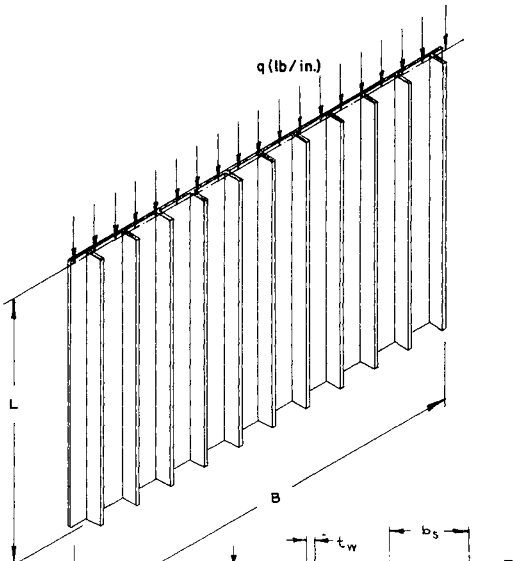

Fig. 10 Integrally stiffened wide-column geometry.

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†† It is recognized that Poisson's ratio for Be is much less than the value associated with the Al and Mg alloys; however, the use of 0.3 will result in negligible error in the analysis that follows.

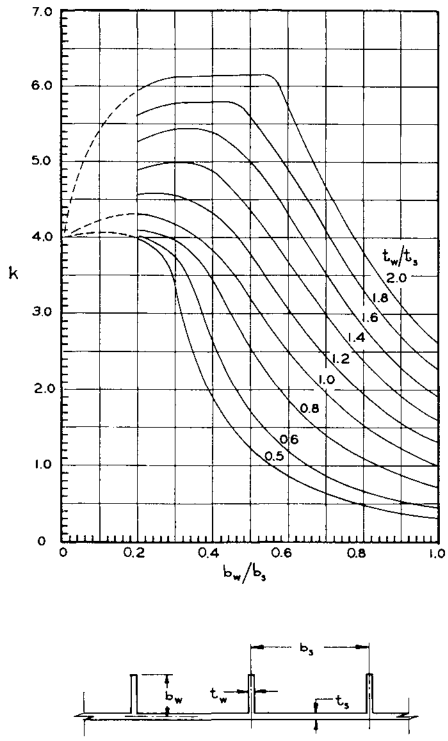

Fig. 11 Coefficients for local buckling mode, web-stiffened plates.

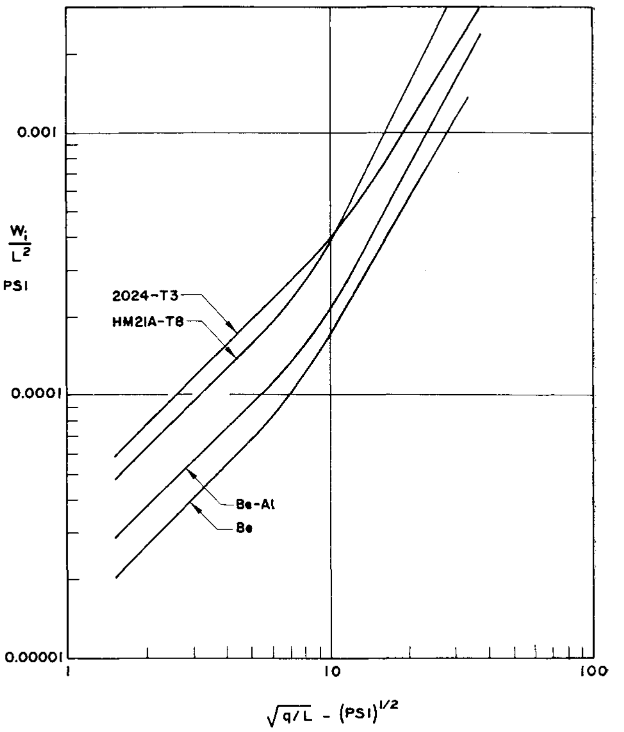

Fig. 13 Structural behavior of integrally stiffened wide-columns.

other reactions) and 10^6 protons/cm^2/sec as the maximum flux that would be encountered either in the Van Allen belt or from solar flares, one derives a fractional transmutation rate for Be of 10^{-18}/sec. Assuming that a fractional transmutation of about 10^{-3} is required to change structural properties, it would take 3×10^7 yr to affect the properties. It is therefore concluded that degradation of Be structural properties in space vehicles will not be a problem.

For many years, nuclear physicists have produced neutrons in the laboratory by bombarding Be metal with alpha particles, deuterons, protons, or x rays. The reason for this is that, although all metals produce neutrons with higher-energy radiations (>10 Mev), only Be produces neutrons with low-energy radiations (~2 Mev). Calculations of neutron production from Be by space radiations were made to demonstrate that this "nuclear" characteristic of Be does not constitute a potential health hazard for space missions. Among the various radiations occurring in space, only the Van Allen belt protons, solar flare protons, and artificial belt electrons are of sufficient intensity and energy to require attention. Further, since the Van Allen belt protons and solar flare protons are similar, only two calculations are needed to survey the problem, one for Van Allen protons and one for artificial belt electrons. During orbital missions on satellites and space stations, these radiations trapped in the earth's magnetic field are of principal interest, and these are of concern only for orbits of several thousand miles altitude. During lunar and planetary missions, solar flare protons constitute the principle radiation of interest.

The calculations involved the following steps: 1) establish external and internal radiation fluxes[10]; 2) establish neutron production cross sections over the energy range of interest[11-13]; 3) calculate neutron production and neutron fluxes; and 4) calculate neutron doses. Data for Van Allen protons are given in Fig. 14. Results of the calculations for several space missions are given in Table 5. In all cases, the dose rates are in the millirad per day region, which are equal to or less than the normal cosmic ray exposure (10–20 millirad/day). Since doses near 100 rad are required for a severe hazard to man, it is obvious that the production of neutrons from Be does not constitute a significant health hazard for missions of reasonable duration.

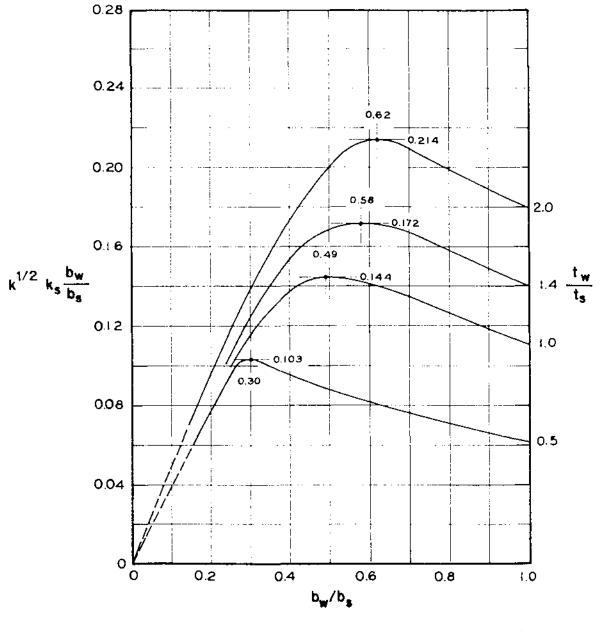

Fig. 12 Variation of shape parameter with b_w/b_s as determined by Freden and White.

Table 5 Secondary neutron dose rates from Be caused by various sources, mrad/day[a]

Mission	Artificial belt electrons	Van Allen protons	Solar flare protons
2000-mile orbit			
Equatorial	0.5	20	...
Polar	0.1	4	...
Interplanetary	...	...	4

[a] For 0.1 Be skin.

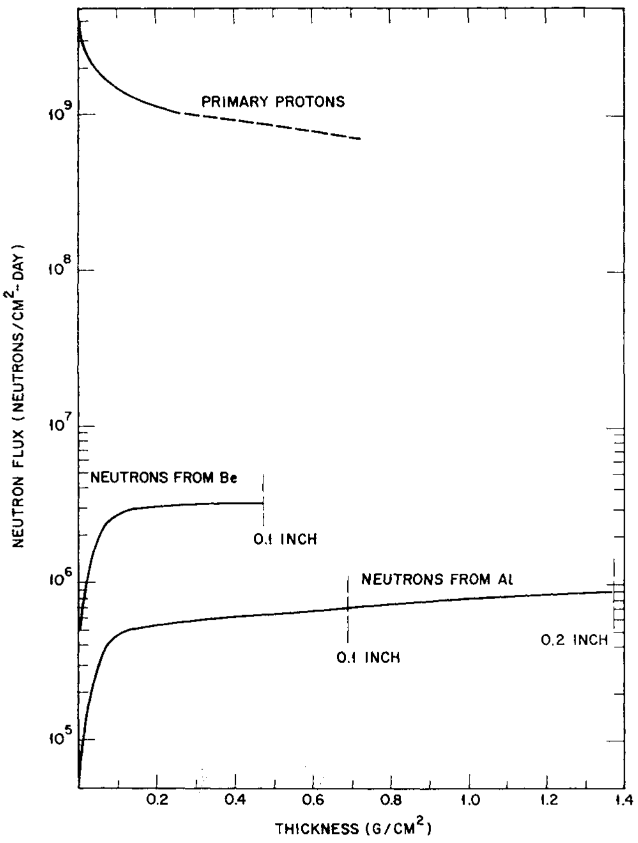

Fig. 14 Neutron and proton fluxes at various depths in Be and Al.

Conclusions

The newly developed Be-Al alloys described offer 1) significant weight savings over Mg and Al alloys in compressively loaded structure, and 2) advantages over Be in the form of improved useful ductility; relative insensitivity to surface damage as compared to Be; freedom from tedious chemical etching after machining; and improved machinability, weldability, fabricability, and forming characteristics, which should result in significantly lower installed cost. The wide ranges of modulus, strength, density, and ductility available in Be-Al alloys make many previously unattainable tradeoffs available to the designer. Since spacecraft structures are lightly loaded, resulting in low loading indexes such that the structure fails in elastic instability, strength above some minimum value is unimportant, thus permitting the metallurgist to process the alloys to an optimum combination of Young's modulus and ductility selected by the designer.

Neither degradation of structural properties by radiation nor the creation of any additional radiation hazard will present a problem when Be or Be-Al is used as structural material for a manned spacecraft.

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