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SUMMARY

The results of an experimental investigation to determine the room-temperature mechanical properties and column behavior of commercially produced Be-38Al alloy tubing are presented. The investigation included tubing in both the as-extruded and annealed conditions. The diameter of the tubes ranged from 0.25 to 0.69 inch (6.4 to 17.5 mm). Wall thickness was 0.020 inch (0.51 mm). Microhardness measurements and metallurgical studies were also performed. The mechanical-property measurements indicated that the tubing was comparable to other forms of the Be-38Al alloy. Column-buckling loads could be satisfactorily predicted by using the tangent modulus, derived from compressive stress-strain curves, in the inelastic column-buckling equation. Column mass-strength comparisons showed that in the plastic range, the as-extruded Be-38Al tubing was more efficient than beryllium tubing. The results also indicated that the Be-38Al tubing could be commercially produced to dimensional tolerances comparable to those of aluminum tubing.

INTRODUCTION

A continuing need exists in aerospace structures for materials which combine high stiffness with low density. Although beryllium has outstanding specific stiffness, its structural application has been limited. This limited application is, in part, due to the brittle and anisotropic behavior of beryllium under biaxial stresses which, among other things, makes it difficult to fabricate and join. A beryllium-aluminum alloy (Be-38Al), which has recently become commercially available, has a specific stiffness intermediate between beryllium and other structural metals. In addition, this new alloy in sheet form is more ductile, is easier to fabricate, and has better impact resistance than beryllium sheet.

Although the mechanical properties of Be-38Al alloy in sheet form have been well documented (see, for example, refs. 1 to 3), only a limited amount of information on extruded tubing is available in the literature. Because of the interest in lightweight tubular structures, an investigation of thin-wall beryllium and beryllium-alloy tubing for lightly loaded truss-type structures has been initiated. Results obtained on the beryllium tubing are reported in reference 4.

The purpose of the present paper is to report the room-temperature mechanical properties and column behavior of commercially produced Be-38Al extruded tubing. The investigation included tubing in both the as-extruded and annealed conditions. The nominal diameter of the tubing ranged from 0.25 to 0.69 inch (6.4 to 17.5 mm). The nominal wall thickness of all tubing was 0.020 inch (0.51 mm).

SYMBOLS

The units used for physical quantities defined in this paper are given both in the U.S. Customary Units and in the International System of Units (SI). Conversion factors relating the two systems are given in reference 5, and those pertinent to the present investigation are presented in appendix A.

A	area, inches^2 (meters^2)
c	column-end-fixity coefficient
D	outside diameter of tube, inches (meters)
E	Young's modulus in tension, pounds force/inch^2 (newtons/meter^2)
E_c	Young's modulus in compression, pounds force/inch^2 (newtons/meter^2)
E_t	tangent modulus, pounds force/inch^2 (newtons/meter^2)
e	total elongation in 2 inches (5 centimeters), percent
e_u	uniform elongation, percent
I	moment of inertia, inches^4 (meters^4)
k	local-buckling constant
L	column length, inches (meters)
P	applied load, pounds force (newtons)

s_D standard deviation of outside diameter of tube

s_t standard deviation of wall thickness

t wall thickness, inches (meters)

W mass, pounds mass (kilograms)

β_1 transverse sensitivity coefficient for longitudinal strain gage

β_2 transverse sensitivity coefficient for transverse strain gage

ϵ strain

ϵ_1 actual longitudinal strain

ϵ_2 actual transverse strain

$\epsilon_{a,1}$ apparent longitudinal strain

$\epsilon_{a,2}$ apparent transverse strain

μ Poisson's ratio

μ_o Poisson's ratio of isotropic bar

ρ radius of gyration, inches (meters)

σ stress, pounds force/inch^2 (newtons/meter^2)

$\bar{\sigma}_{max}$ average stress at maximum compressive load, pounds force/inch^2 (newtons/meter^2)

ω density, pounds mass/inch^3 (kilograms/meter^3)

Subscripts:

cc local buckling

cp	compressive proportional limit
cr	buckling
cy	0.2-percent offset compressive yield
e	effective
m	mean
max	maximum
min	minimum
n	nominal
tp	tensile proportional limit
tu	tensile ultimate
ty	0.2-percent offset tensile yield

A bar over a symbol indicates average value.

EXPERIMENTAL PROCEDURES

Materials

The Be-38Al tubing (38-percent aluminum by weight) used in this investigation was furnished by the supplier in both the as-extruded and annealed conditions. Delivery of the tubing was completed in the fall of 1966. The tubing diameter ranged from 0.2500 to 0.6875 inch (6.35 to 17.46 mm), and the nominal wall thickness was 0.020 inch (0.508 mm). The nominal outside diameters, the three heat and lot numbers, and chemical compositions of the tubing are presented in table I.

All tubing was extruded from hollow-core "canned billets." A steel mandrel was used to fill the cored billet before extrusion. The canned billet and the extrusion tooling were heated to 850° F (730° K) prior to extrusion. A reduction ratio of 25:1 was used for all of the tubing. The extrusion ram speed was 11 in./min (4.6×10^{-3} m/s). After extrusion, the tubing was dejacketed in nitric acid. The tubing was then resistance heated and stretch straightened. Tubing supplied in the annealed condition was heat treated after straightening for 24 hours at 1100° F (865° K) in a vacuum of less than 0.1 torr (13 N/m^2).

The specified dimensional tolerances on outside diameter, wall thickness, and straightness for both the as-extruded and annealed tubing are presented in table II. These tolerances are comparable to those for the 5000-series aluminum alloys presented in ASTM designation B 221-67 (ref. 6).

Metallurgical Examinations

Metallurgical examinations included macroscopic and microscopic observations and microhardness measurements. The tubing was examined macroscopically both in the as-received condition and after etching in a chromic acid, hydrofluoric acid, and water solution ($HF\text{-}Cr_2O_3\text{-}H_2O$) to remove approximately 0.010 inch (0.25 mm) of the outside diameter. Standard metallographic procedures were used to prepare specimens for microstructure examinations. Polished sections were prepared in both the longitudinal and transverse directions of the tubing. Knoop microhardness determinations were made on polished sections with a standard microhardness machine. The penetrator load was 100 grams, and the dwell time was 15 seconds. Each reported average microhardness number was based on 10 microhardness determinations.

Dimensional Measurements

The outside diameter, wall thickness, and straightness of the Be-38Al tubing were measured to verify conformance to the specified tolerances (table II) and to provide an estimate of the variability of diameter, wall thickness, area, and moment of inertia. At least six measurements of outside diameter and wall thickness were used to calculate average values for each nominal diameter of tubing. Typically, measurements were made at three equally spaced sections on the tubes which were from 1 to 10 inches (25 to 250 mm) long and at five equally spaced sections on tubes which were longer than 10 inches (250 mm). The variability in diameter was calculated by using the average diameter determined at each measured section as a single observation. Wall-thickness variability was calculated in a similar manner. Assuming a circular cross section and a constant wall thickness, the area and moment of inertia of each measured section were calculated and used to determine the variability of these two section properties. Straightness measurements were made on tubes greater than 3 inches (76 mm) in length. Additional details of the equipment and procedures used for the dimensional measurements are presented in reference 4.

Mechanical-Property Tests

Tensile and compressive mechanical-property tests were performed at room temperature in a 120 000-lbf-capacity (535-kN) universal hydraulic testing machine.

The tensile specimens were prepared by adhesively bonding end fittings to the tubing. To preclude specimen failure at the end fittings, the bonded tensile specimens were etched in a $HF-Cr_2O_3-H_2O$ solution to remove a minimum of 0.010 inch (0.25 mm) from the outside diameter of the specimen. The length of the reduced section was at least 6 times the nominal diameter of the specimen. Carefully alined precision-machined grip assemblies were used for tensile tests to minimize loading eccentricity.

Compressive specimens were tested in the as-received condition. The ends of these specimens had been ground plane, smooth, and perpendicular to within 0.25° of an axial line passing through the centroids of the specimen ends. The length-to-diameter ratio of the compression specimens was approximately 4. The compression specimens were supported on hardened steel disks. Annealed aluminum washers were inserted between the specimen ends and the steel disks. The plastic deformation of the aluminum washers helped to distribute the load uniformly on the specimen.

To prevent possible contamination of the laboratory air with toxic Be-38Al dust, both the tensile and compressive specimens were enclosed in a protective cylindrical sleeve during testing. This sleeve was made from multiple layers of 0.008-inch (0.2-mm) latex sheet, wound around the steel support blocks of the compressive specimens and the aluminum end fittings of the tensile specimens. The sleeves were sealed with masking tape. After testing, the sleeves were removed while the assembly was immersed in acetone.

In both the tensile and compressive tests, strain was measured with foil-type strain gages adhesively bonded to the specimens. Each strain-gage assembly included strain-sensing elements in both the longitudinal and transverse directions. The gage assemblies were equally spaced about the circumference of each specimen. Two such assemblies were bonded to each 0.250-inch-diameter (6.35-mm) specimen. Four gage assemblies were bonded to each specimen over 0.250 inch (6.35 mm) in diameter. The electrical outputs of the strain gages and of a load-indicating deflectometer attached to the load dial of the testing machine were recorded on magnetic tape. Each electrical signal was recorded at approximately 0.5-second intervals up to the yield strain and at approximately 2.0-second intervals thereafter.

The nominal strain rate for the mechanical-property tests was 0.0015 per minute up to the 0.2-percent offset yield strain and 0.015 per minute thereafter. The strain rate was manually controlled throughout each test. The instantaneous strain rate was monitored by comparing the output of a longitudinal strain gage on a strip-chart recorder with lines drawn on the recorder paper at the desired strain rate.

Finely scribed pencil lines at 0.40-inch (10-mm) intervals along the specimen were used to make elongation measurements on the tensile specimen. Both elongation in 2 inches (5 cm) and uniform elongation were measured. Uniform elongation is the amount of residual plastic strain in the unfractured portions of a tensile specimen. Uniform elongation does not include the region of the specimen near the fracture and was determined by averaging the residual plastic strain in each portion of a fractured tensile specimen.

Data from the mechanical-property tests were reduced by means of a digital computer and associated automatic plotting equipment. To determine the tangent-modulus curves, short segments (seven consecutive data points) of the stress-strain curves were successively fitted to a second-order polynominal equation by the method of least squares. The first derivative of the fitted equation was used to calculate tangent modulus at the center of the fitted segment. To determine Poisson's ratio, correction of the indicated strains for transverse strain was necessary. By using the procedures presented in reference 7 for this type of correction, the following equations were developed to account for the different transverse sensitivity coefficients in the longitudinal and transverse gages of the strain-gage assemblies:

$$\epsilon_1 = \frac{\epsilon_{a,1}\left(1 - \mu_o\beta_1\right) - \beta_1\epsilon_{a,2}\left(1 - \mu_o\beta_2\right)}{1 - \beta_1\beta_2}$$

$$\epsilon_2 = \frac{\epsilon_{a,2}\left(1 - \mu_o\beta_2\right) - \beta_2\epsilon_{a,1}\left(1 - \mu_o\beta_1\right)}{1 - \beta_1\beta_2}$$

where $\epsilon_{a,1}$ and $\epsilon_{a,2}$ are the apparent strains in the longitudinal and transverse gages, respectively; μ_o is the Poisson's ratio of the isotropic bar on which the gages were calibrated; and β_1 and β_2 are the transverse sensitivity coefficients of the longitudinal and transverse gages, respectively. The reported Poisson's ratio for each specimen represents an average of the Poisson's ratios determined from each gage assembly on a specimen. Additional details of the equipment and procedures used for the mechanical-property tests are presented in reference 4.

Column Tests

Column tests were also made at room temperature in a 120 000-lbf-capacity (535-kN) universal hydraulic testing machine. Column specimens ranged in length from 3 to 30 inches (76 to 760 mm) and were tested in the as-received condition. The ends of the columns were ground to the same tolerances as the ends of the compression specimens. Four foil-type strain gages were bonded to the center of each column. These gages were equally spaced about the circumference of the column and were used to establish an initial elastic modulus. The columns were enclosed in a protective latex-sheet sleeve and were tested with fixed ends.

Steel tubes with stiffness comparable to that of the Be-38Al columns were used to establish the column-end-fixity coefficient c by the method outlined in reference 8. The experimental buckling stress was taken as the average stress at the maximum compressive load $\bar{\sigma}_{max}$. Additional details of the column testing equipment and procedures are presented in reference 4.

A graphical procedure which employed the tangent-modulus inelastic column equation,

$$\sigma_{cr} = \frac{\pi^2 E_t}{\left(\frac{L_e}{\rho}\right)^2}$$

where

$$\left(\frac{L}{L_e}\right)^2 = c = 3.94$$

was used to calculate the theoretical column-buckling stress over a range of effective slenderness ratios L_e/ρ for each type of Be-38Al alloy tubing. The theoretical column-buckling stress σ_{cr} at a given slenderness ratio was calculated by using the average value of compressive tangent modulus for all of the tubing in a given heat-treatment condition.

RESULTS AND DISCUSSION

Metallurgical Examinations

Macrostructure.- Both the as-extruded and the annealed tubes typically exhibited a dull matte appearance which is characteristic of an etched surface (fig. 1). Some of the tubes in the as-received condition contained minor surface defects such as small pits and very shallow longitudinal grooves. Often these grooves were formed by a series of closely spaced small pits. When tensile specimens were etched, these surface defects were easily detected (figs. 2(a) and (b)). One of the as-extruded 0.250-inch-diameter (6.35-mm) tensile specimens exhibited a "rattlesnake" surface after etching (fig. 2(c)) which was not evident prior to etching.

Microstructure.- Typical samples of longitudinal and transverse microstructure of the as-extruded and the annealed tubing are presented in figures 3 and 4, respectively. The gray areas are beryllium and the white areas are aluminum. In both the as-extruded and the annealed conditions, the aluminum is somewhat elongated in the longitudinal direction and essentially randomly dispersed in the transverse direction. The major difference between the microstructures of the two types of tubing is an apparent coarsening of the aluminum (i.e., greater separation of the aluminum "islands") in the annealed material. The annealed microstructures are similar to those of the annealed extruded bar described in reference 1. Small angular inclusions (figs. 3(a) and 4(b)) were occasionally noted. Similar inclusions were tentatively identified in reference 9 as beryllium carbide.

Microhardness.- The results of the microhardness measurements are presented in table III. As expected, the as-extruded tubing was somewhat harder than the annealed tubing. On the basis of the confidence intervals listed in table III, there do not appear to be any significant differences in microhardness as a function of direction. This isotropic behavior is in contrast to the anisotropic microhardness of extruded thin-wall beryllium tubing (ref. 4). Except for the 0.250-inch-diameter (6.35-mm) tubing in the annealed condition, the microhardness values of all tubing in a given heat treatment were essentially the same. The microhardness values of two different 0.250-inch-diameter (6.35-mm) annealed tubes were significantly different from each other and from the microhardness values of the other annealed tubes. No completely satisfactory explanation for this difference in microhardness could be found. The somewhat higher oxide content of these tubes (table I) may have been responsible for their increased hardness. This explanation, however, is not consistent with the fact that the microhardness of the as-extruded tubes made with this lot of material was not significantly higher than the microhardness of the as-extruded tubes made from material with a lower oxide content.

Dimensional Measurements

The measurements of diameter and wall thickness, normalized with respect to their specified nominal values, are summarized in table IV. These normalized data and similar data on the calculated area and moment of inertia are presented in figure 5. As expected, on a percentage basis wall-thickness variations were much greater than diameter variations. The standard deviation of diameter was less than 2 percent of the specified diameter for all of the tubes, and the standard deviation of wall thickness ranged from 1.5 to 7.5 percent of the mean wall thickness. Of more importance is the fact that the average wall thickness was as much as 12 percent below the specified value. The average values of the computed section properties A and I reflect the variation in wall thickness exhibited by the tubing. It is interesting to note that extruded beryllium tubing (ref. 4) exhibited similar variations in wall thickness, although in all cases the average wall thickness of the beryllium tubing was in excess of that specified. It should also be noted that the dimensional tolerances for both the Be-38Al tubes and the beryllium tubes were comparable to those used for 5000-series aluminum alloys. Consequently, as was the case for the beryllium tubes, the maximum deviation from any specified dimension in the Be-38Al tubing is comparable to that which could be expected in 5000-series aluminum tubing.

The annealing heat treatment did not appear to alter significantly the dimensional characteristics of the tubing. Both types of tubing exhibited similar increases in the normalized values of average diameter and average wall thickness as a function of increasing diameter.

Mechanical-Property Tests

The results of the mechanical-property tests are summarized in table V. The results for individual specimens are presented in table VI for the tensile tests and in table VII for the compressive tests. The tensile strengths of the as-extruded tubing showed considerable variation over the range of diameters tested. All other measured mechanical properties for the tubing of a given heat treatment showed little variation as a function of diameter.

Strengths and proportional limit.- As expected, the annealed tubing had lower values of strength than the as-extruded tubing (table V). Typical stress-strain curves for these two types of tubing are shown in figure 6. Both the compressive proportional limits and the compressive yield strengths of the tubing were usually somewhat lower than the comparable tensile values. The lower compressive proportional limits and yield strengths are probably due to the procedures used to straighten these tubes after extrusion.

The data for the as-extruded tubing (table V) indicated a general trend of increasing proportional limits and yield strengths as a function of increasing diameter. This trend is shown graphically in figure 7. This trend, however, was reversed in the annealed tubing; that is, the proportional limits and yield strengths decreased slightly as a function of increasing diameter (fig. 8). The greater susceptibility of the stronger, larger diameter tubing to the annealing heat treatment, in terms of the reduction in yield strength, is consistent with a similar observation reported in reference 2 for as-rolled Be-38Al sheet exposed to heat treatment at 1100° F (865° K).

The data on tensile yield strength, tensile ultimate strength, and elongation presented in table V are in general agreement with similar data presented in reference 2 for Be-38Al extruded mill forms. Both extruded bar and sheet in the annealed condition have a lower yield strength in compression than in tension (ref. 1).

Elastic modulus and Poisson's ratio.- The average values of elastic modulus for the Be-38Al tubing ranged from 28.1×10^6 to 30.4×10^6 psi (194 to 210 GN/m^2). (See table V.) These values are in excellent agreement with the values reported in reference 2 for extruded bar and sheet. No consistent differences in elastic modulus, either as a function of diameter or as a function of heat treatment, were apparent. This result is in contrast to the reduction in elastic modulus which was observed in reference 3 after heat treatment of as-extruded Be-38Al sheet material. The stress dependence of the tangent modulus is presented in figure 9. These typical curves illustrate the lower proportional limits of the annealed tubing and its rapid decrease in tangent modulus for stresses above the proportional limit. This figure also reflects the minor differences in the shapes of the tensile and compressive stress-strain curves in each heat-treatment condition.

The stress dependence of Poisson's ratio for the Be-38Al tubing is shown in figure 10. Above the proportional limit, both types of tubing exhibited the expected increase in Poisson's ratio. This increase occurred more rapidly in the annealed tubing as a function of stress than in the as-extruded tubing. In addition, the annealed tubing typically exhibited a higher maximum value of Poisson's ratio than the as-extruded tubing. The differences in the shapes of the curves in figure 10 for the tensile and compressive specimens were reproducible and are considered characteristic.

Failure modes.- In both the as-extruded and annealed tubing, tensile fractures typically occurred at right angles to the longitudinal axis of the tubing (fig. 11). The annealing heat treatment did not affect the shape of the fracture. However, the annealing treatment increased the average elongation at failure (table V). The small longitudinal grooves or pits noted in the etched tensile specimens did not seem to affect the strength or the elongation at failure of either the as-extruded or the annealed tubes. The single 0.250-inch-diameter (6.35-mm) tensile specimen with the rattlesnake surface had a very low strength (30.1 ksi or 208 MN/m^2) and almost no elongation. This specimen is not reported in table VI.

The failure modes of the compression specimens were different from those of the tensile specimens and suggested that the annealed tubing was less anisotropic than the as-extruded tubing. The as-extruded compression specimens developed longitudinal cracks when the maximum compressive stress was attained (fig. 12(a)). These longitudinal cracks were induced by the circumferential tensile stresses which were developed near the restrained ends of the short compression specimens. The annealed compression specimens (fig. 12(b)) continued to deform after the maximum compressive stress was attained and typically sustained a considerable amount of circumferential plastic strain without developing longitudinal cracks. Even after an annealing heat treatment, Be-38Al extrusions have a crystallographic texture similar to that of beryllium extrusion (ref. 9). Consequently, it is reasonable to assume that the behavior of the annealed tubing in compression was less anisotropic than that of the as-extruded tubing because of the decrease in preferred orientation which occurred as a result of the annealing heat treatment.

Column Tests

The results of the column tests are presented in table VIII. This table also presents the experimentally determined elastic modulus and the calculated buckling stress

σ_{cr} for the columns. No corrections were made for the lack of column straightness. The average value of the initial elastic modulus of the columns was 28.5×10^6 psi (197 GN/m^2). This compares closely with the average of 28.8×10^6 psi (198 GN/m^2) from the mechanical-property tests.

In figures 13 and 14, the results of the column tests are compared with the calculated buckling stresses. The elastic Euler equation and the Engesser tangent-modulus equation for both the average value of tangent modulus and the range in tangent modulus obtained from the compression tests were used in this calculation. For both the as-extruded and annealed tube columns, the agreement between the predicted and the experimental column behavior is satisfactory. It should be noted that the prediction band for the as-extruded columns (fig. 13) includes the variation in compressive properties which was observed for the four different diameters of tubing. Although the results of the annealed tube columns (fig. 14) are well within the predicted range of column failure stress, both the data scatter and the range of the prediction band reflect the lower reproducibility of the compressive mechanical properties of the annealed tubing.

The effects of the low proportional limit, as compared with the yield strength, exhibited by the Be-38Al tubing are well illustrated by comparing the Engesser tangent-modulus prediction band with the elastic Euler curve. In the case of the annealed tube columns, for instance, the use of the tangent-modulus inelastic column equation for stresses as low as 15 ksi (103 MN/m^2) is necessary to predict the column-buckling stress.

Column-Efficiency Comparisons

In this section, the structural efficiency of the Be-38Al columns tested in the present study is compared with the efficiency of minimum-mass Be-38Al columns. The structural efficiency of the Be-38Al tubing is also compared with the structural efficiencies of aluminum and beryllium for use in minimum-mass thin-wall tube columns of circular cross section. The mass-strength equations utilized in these comparisons are presented in appendix B. The material properties and compressive tangent-modulus curves used for the comparisons are shown in table IX and figure 15, respectively. The material properties of the aluminum (7075-T6) and beryllium tubing were taken from references 10 and 4, respectively. The selected beryllium tubing is referred to in reference 4 as type BL.

Mass-strength data for the as-extruded Be-38Al columns utilized in the present study are compared with the mass-strength data for minimum-mass ($\sigma_{cr} = \sigma_{cc}$) as-extruded Be-38Al columns in figure 16. The symbols show values obtained from the column tests reported herein, and the curves show calculated results. In addition to the minimum-mass ($\sigma_{cr} = \sigma_{cc}$) curve, calculated curves for the maximum and minimum D_m/t values of the columns that were tested are also shown in figure 16. These two curves provide a frame of reference for the column results and show D_m/t "cutoffs" for columns which are restricted by minimum-gage considerations to values of D_m/t which are less than those of a minimum-mass column. (See appendix B.)

Figure 16 shows the wide range of the structural index P/L^2 that was covered in the column tests. In addition, this figure clearly shows that many of the tested columns were inefficient when compared with a minimum-mass Be-38Al column, particularly at the lower values of the structural index. Even though the wall thickness was 0.020-inch (0.51 mm), the columns were severely restricted by minimum gage limitations at the lower values of the structural index $\left(P/L^2 < 10 \text{ lbf/in}^2 \text{ or } 69 \text{ kN/m}^2\right)$. For example, the mass corresponding to the columns tested at a structural index of 0.1 lbf/in^2 (0.69 kN/m^2) was 5 times as great as the mass of comparable minimum-mass $(\sigma_{cr} = \sigma_{cc})$ columns.

In the rest of this section, the calculated column efficiency of Be-38Al tubing is compared with that of aluminum and beryllium tubing. The compressive tangent-modulus curves shown in figure 15 clearly indicate that the four materials change in relative stiffness as the stress level increases. Figure 15 does not, however, provide an adequate materials comparison for tube columns. This figure does not reflect the density of the materials and does not allow a direct comparison of the materials for a given set of column design conditions P and L. A more useful comparison of the relative efficiencies of these materials for tube-column applications is shown in figure 17. In this figure, the column efficiency of the Be-38Al tubing is compared with the efficiencies of aluminum and beryllium tubing on a column mass-strength basis. The curves are for minimum-mass $(\sigma_{cr} = \sigma_{cc})$ pinned-end columns and were obtained from equations (B6) and (B7) (appendix B). As would be expected from the curves in figure 15, the beryllium tubing is most efficient in the elastic range $\left(\text{low values of } P/L^2\right)$. Because of the rapid decrease in the tangent modulus with increasing stress in the beryllium (fig. 15), the as-extruded Be-38Al alloy is the most efficient material at values of P/L^2 greater than 0.1 lbf/in^2 (0.69 kN/m^2). For values of P/L^2 greater than 1 lbf/in^2 (6.9 kN/m^2), the annealed Be-38Al alloy is as efficient as the beryllium. However, both beryllium and annealed Be-38Al alloy become less efficient than aluminum for values of P/L^2 greater than 10 lbf/in^2 (69 kN/m^2).

In summary, of the materials considered in this comparison, the as-extruded Be-38Al tubing is the most efficient on a mass-strength basis over a wide range of the column structural index P/L^2.

CONCLUDING REMARKS

The room-temperature mechanical properties and column behavior of commercially produced thin-wall Be-38Al tubing in both the as-extruded and annealed heat-treatment conditions have been investigated. The results indicated that the Be-38Al alloy tubing could be commercially produced to dimensional tolerances comparable to those of aluminum tubing. The results of the mechanical-property tests, which include three lots and three heats of material, indicated that the properties of the tubing were comparable to those reported in the literature for extruded bar and sheet products of the Be-38Al alloy. The column behavior of the tubing could be satisfactorily predicted by using the Euler-Engesser relationship. The column tests also demonstrated that the use of the tangent-modulus inelastic column equation was necessary at stresses as low as 15 ksi (103 MN/m^2) for the annealed tubing because of its low proportional limit. Column mass-strength comparisons showed that in the plastic range, as-extruded Be-38Al alloy is more efficient than beryllium.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., January 10, 1969,
124-08-01-05-23.

APPENDIX A

CONVERSION OF U.S. CUSTOMARY UNITS TO SI UNITS

The International System of Units (SI) was adopted by the Eleventh General Conference on Weights and Measures, Paris, 1960. (See ref. 5.) Factors required for converting the U.S. Customary Units used herein to the International System of Units (SI) are given in the following table:

Physical quantity	U.S. Customary Unit	Conversion factor (*)	SI Unit
Mass	lbm	0.4536	kilograms (kg)
Length	in.	0.0254	meters (m)
Velocity	in./min	4.23×10^{-4}	meters per second
Temperature . . .	(^{o}F + 460)	5/9	degrees Kelvin (^{o}K)
Density	lbm/in^3	27.68×10^3	kilograms per cubic meter (kg/m^3)
Load	lbf	4.448	newtons (N)
Pressure	torr	1.333×10^2	newtons per square meter (N/m^2)
Stress	psi = lbf/in^2	6895	newtons per square meter (N/m^2)
	ksi = kips/in^2	6895×10^3	newtons per square meter (N/m^2)

*Multiply value given in U.S. Customary Unit by conversion factor to obtain equivalent value in SI Unit.

Prefixes to indicate multiple of units are as follows:

Prefix	Multiple
milli (m)	10^{-3}
kilo (k)	10^3
mega (M)	10^6
giga (G)	10^9

APPENDIX B

MASS-STRENGTH EQUATIONS FOR THIN-WALL TUBE COLUMNS OF CIRCULAR CROSS SECTION

The efficiency of a minimum-weight column can be expressed in terms of a mass index W/L^3 and a structural or loading index P/L^2 (ref. 11). The relationship between these two indices as determined by equating the column-buckling stress σ_{cr} to the local-buckling stress σ_{cc}. For the purposes of the present discussion of thin-wall tube columns, the following expressions from reference 12 were utilized:

$$\sigma_{cr} = \frac{c\pi^2 E_t D_m{}^2}{8L^2} \tag{B1}$$

$$\sigma_{cc} = k\left(E_c E_t\right)^{1/2} \frac{t}{D_m} \tag{B2}$$

By utilizing the relationship for the area of a thin-wall tube of circular cross section,

$$A = \frac{P}{\sigma} = \pi D_m t$$

equation (B1) can be solved in terms of the structural index:

$$\frac{P}{L^2} = \frac{8\sigma_{cr}{}^2}{c\pi E_t} \frac{t}{D_m} \tag{B3}$$

Setting $\sigma = \sigma_{cr} = \sigma_{cc}$ and eliminating t/D_m between equations (B2) and (B3) yields

$$\frac{P}{L^2} = \frac{8\sigma^3}{c\pi k E_t{}^{3/2} E_c{}^{1/2}} \tag{B4}$$

The mass of a column with uniform cross section is

$$W = \omega A L = \omega \frac{P}{\sigma} L \tag{B5}$$

Solving equation (B4) for σ and substituting the results into equation (B5) yields

$$\frac{W}{L^3} = \frac{2}{(c\pi k)^{1/3}} \frac{\omega}{E_c{}^{1/6} E_t{}^{1/2}} \left(\frac{P}{L^2}\right)^{2/3} \tag{B6}$$

This equation is the structural-efficiency relationship of a minimum-mass column for $\sigma < \sigma_{cy}$. For $\sigma = \sigma_{cy}$, the column-efficiency relationship becomes

$$\frac{W}{L^3} = \frac{\omega}{\sigma_{cy}} \frac{P}{L^2} \tag{B7}$$

For a minimum-mass tube column $\left(\sigma_{cr} = \sigma_{cc}\right)$, reference 11 shows that

$$\left(\frac{D_m}{t}\right)_{\sigma_{cr}=\sigma_{cc}} = 2\left(\frac{k^2 E_c}{c\pi \frac{P}{L^2}}\right)^{1/3} \tag{B8}$$

Equation (B8) shows that for a given material, the proportions D_m/t of a minimum-mass tube column are a function of the structural index P/L^2.

Minimum wall thickness (minimum gage) is often a controlling factor in the design of a tube column, particularly for low values of the structural index P/L^2. Therefore, it is appropriate to consider the efficiency of a tube column for which minimum-gage restrictions preclude the design of a minimum-mass column. Solving equation (B3) for σ_{cr} and substituting the results into equation (B5) yields

$$\frac{W}{L^3} = \left(\frac{8}{c\pi}\right)^{1/2}\left(\frac{D_m}{t}\right)^{-1/2} \frac{\omega}{E_t^{1/2}}\left(\frac{P}{L^2}\right)^{1/2} \tag{B9}$$

Equation (B9) is the structural-efficiency relationship for tube columns which, because of minimum-gage restrictions, do not have minimum-mass proportions; that is,

$$\frac{D_m}{t} < \left(\frac{D_m}{t}\right)_{\sigma_{cr}=\sigma_{cc}}$$

On a column mass-strength plot, equation (B9) yields D_m/t cutoff curves which merge with curves obtained from equation (B6).

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TABLE I.- CHEMICAL COMPOSITION OF EXTRUDED Be-38Al ALLOY TUBING[a]

[0.020-inch (0.508-mm) nominal wall thickness]

Condition	Nominal outside diameter, in.	Nominal outside diameter, mm	Heat number	Lot number	Composition, percent by weight: Be	BeO	Al_2O_3	Fe	Si	Mg	C	Al
As-extruded	0.2500	6.35	331-H	65-9	62.6	0.67	2.42	0.070	0.049	0.012	0.049	Bal.
	.6875	17.46										
	0.4375	11.11	438-H	65-10	63.5	0.39	1.02	0.062	0.063	0.007	0.043	Bal.
	.5625	14.29										
Annealed	0.2500	6.35	331-H	65-9	62.6	0.67	2.42	0.070	0.049	0.012	0.049	Bal.
	0.4375	11.11	255-H	65-2	64.0	0.50	1.00	0.075	0.050	0.0035	0.049	Bal.
	.5625	14.29										
	.6875	17.46										

[a]Information furnished by supplier.

TABLE II.- DIMENSIONAL TOLERANCES FOR EXTRUDED Be-38Al ALLOY TUBING

[0.020-inch (0.508-mm) nominal wall thickness]

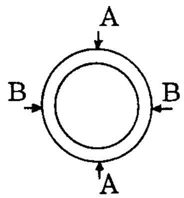
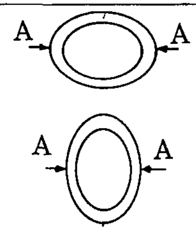
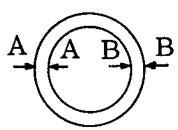
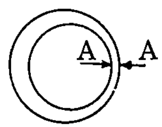
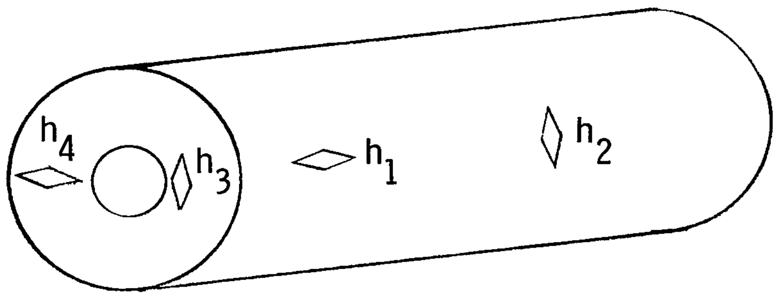
Variation		Variation definition		Tolerance
Outside diameter	Size		Maximum deviation of mean diameter at any section along tube from specified diameter: deviation is difference between $\frac{1}{2}$(AA + BB) and specified diameter	±0.010 in. (±0.254 mm)
	Ovalness		Maximum deviation of diameter at any point along tube from specified diameter: deviation is difference between AA and specified diameter	±0.020 in. (±0.508 mm)
Wall thickness	Thickness		Maximum deviation of mean wall thickness at any section along tube from specified thickness: deviation is difference between $\frac{1}{2}$(AA + BB) and specified wall thickness	±0.006 in. (0.152 mm)
	Eccentricity		Maximum deviation of wall thickness at any section from specified wall thickness: deviation is difference between AA and mean wall thickness	±10 percent of mean wall thickness
Straightness		Maximum deviation from straight at any point along length of tube: deviation is measured after rotating finished tube through 360° and with ends resting on a plane surface		±0.83 percent of length

TABLE III.- MICROHARDNESS OF EXTRUDED Be-38Al ALLOY TUBING

[0.020-inch (0.508-mm) nominal wall thickness]



Condition	D_n		h_1		h_2		h_3		h_4	
	in.	mm	KHN_{100} (a)	CI (b)	KHN_{100} (a)	CI (b)	KHN_{100} (a)	CI (b)	KHN_{100} (a)	CI (b)
As-extruded	0.2500	6.35	204.4	4.8	188.9	7.7	197.6	4.3	212.9	5.0
	.4375	11.11	193.4	5.4	185.8	7.2	193.7	4.7	221.3	8.7
	.5625	14.29	207.8	6.1	207.0	5.9	194.5	7.8	213.7	8.4
	.5625	14.29	203.9	9.9	208.3	4.2	----	---	----	---
	.6875	17.46	199.8	11.4	200.6	10.0	196.8	3.9	213.6	12.2
Annealed	0.2500	6.35	187.7	4.2	186.8	5.8	184.1	2.9	196.5	4.5
	.2500	6.35	166.5	4.1	172.4	3.5	157.9	1.8	164.6	1.8
	.4375	11.11	149.6	6.8	142.6	6.1	138.8	3.7	154.4	4.6
	.5625	14.29	141.5	6.2	147.6	4.8	137.1	6.4	144.6	7.4
	.6875	17.46	145.0	2.2	139.8	4.0	134.1	4.4	146.1	7.6

[a]Knoop microhardness number determined by using a 100-gram mass.

[b]Half-width of 95-percent confidence interval based on 10 determinations of microhardness.

TABLE IV.- SUMMARY OF DIMENSIONAL MEASUREMENTS ON EXTRUDED Be-38Al ALLOY TUBING

[0.020-inch (0.508-mm) nominal wall thickness]

Condition	D_n, in.	D_n, mm	$\frac{\bar{D}}{D_n}$	$\frac{D_{max}}{D_n}$	$\frac{D_{min}}{D_n}$	$\frac{S_D}{D_n}$	$\frac{\bar{t}}{t_n}$	$\frac{t_{max}}{t_n}$	$\frac{t_{min}}{t_n}$	$\frac{S_t}{t_n}$	Number of observations	Number of tubes
As-extruded	0.2500	6.35	0.995	1.012	0.970	0.008	0.880	1.00	0.770	0.060	103	32
	.4375	11.11	1.001	1.015	.993	.005	.930	1.06	.84	.050	166	43
	.5625	14.29	1.006	1.011	1.001	.002	1.020	1.10	.96	.035	128	32
	.6875	17.46	1.008	1.016	1.001	.004	1.055	1.18	.98	.045	128	33
Annealed	0.2500	6.35	0.997	1.003	0.975	0.007	0.910	0.97	0.75	0.075	28	11
	.4375	11.11	.999	1.000	.996	.001	.915	.95	.88	.015	33	11
	.5625	14.29	1.002	1.004	.997	.002	.965	1.02	.92	.030	30	10
	.6875	17.46	1.005	1.009	1.002	.002	1.010	1.06	.94	.025	51	17

TABLE V.- SUMMARY OF ROOM-TEMPERATURE MECHANICAL PROPERTIES OF EXTRUDED Be-38Al ALLOY TUBING

[0.0200-inch (0.508-mm) nominal wall thickness]

D_n		σ_{cp}		σ_{tp}		σ_{ty}		σ_{tu}		σ_{cy}		E		E_c		μ_{tp}	μ_{cp}	e_u	e
in.	mm	ksi	MN/m^2	ksi	MN/m^2	ksi	MN/m^2	ksi	MN/m^2	ksi	MN/m^2	psi	GN/m^2	psi	GN/m^2				
As-extruded																			
0.2500	6.35	21	140	22	150	---	---	66.2	456	71.2	491	28.9×10^6	199	28.5×10^6	197	0.122	0.134	<1	<1
.4375	11.11	23	160	25	170	---	---	65.0	448	74.7	515	28.7	198	28.4	196	.106	.114	<1	<1
.5625	14.29	24	170	28	200	78.8	543	81.3	561	76.9	530	28.6	197	28.4	196	.102	.111	<1	<1
.6875	17.46	24	170	26	180	81.3	561	85.6	590	78.0	538	29.0	200	28.8	199	.107	.115	<1	<1
Annealed																			
0.2500	6.35	19	130	17	120	50.1	346	56.8	392	55.7	384	28.7×10^6	198	28.5×10^6	197	0.120	0.107	2	2
.4375	11.11	17	120	15	100	50.3	347	53.4	368	48.6	335	29.1	201	28.6	197	.112	.114	2	2
.5625	14.29	16	110	15	100	48.8	336	60.3	416	43.8	302	30.4	210	28.2	194	.110	.120	4	5
.6875	17.46	15	100	16	110	48.6	335	54.5	376	43.4	299	29.3	202	28.1	194	.120	.117	2	3

TABLE VI.- RESULTS OF ROOM-TEMPERATURE TENSILE TESTS ON EXTRUDED Be-38Al ALLOY TUBING

[0.020-inch (0.508-mm) nominal wall thickness]

(a) As-extruded

Specimen	D_n		σ_{tp}		σ_{ty}		σ_{tu}		E		μ_{tp}	e_u	e
	in.	mm	ksi	MN/m^2	ksi	MN/m^2	ksi	MN/m^2	psi	GN/m^2			
1	0.2500	6.35	20	140	---	---	61.8	426	28.0×10^6	193	0.120	<1	<1
2	↓	↓	26	180	---	---	60.8	419	29.0	200	.120	<1	<1
3	↓	↓	22	150	77.4	534	80.5	555	29.9	206	.116	<1	<1
4	↓	↓	20	140	---	---	61.5	424	28.6	197	.132	<1	<1
Average			22	150	---	---	66.2	456	28.9×10^6	199	0.122	<1	<1
5	0.4375	11.11	24	170	---	---	75.0	517	28.6×10^6	197	0.102	<1	<1
6	↓	↓	26	180	---	---	62.7	432	28.8	199	.104	<1	<1
7	↓	↓	24	170	---	---	60.8	419	28.6	197	.108	<1	<1
8	↓	↓	26	180	---	---	58.4	403	29.0	200	.105	<1	<1
9	↓	↓	24	170	---	---	68.0	469	28.4	196	.109	<1	1
Average			25	170	---	---	65.0	448	28.7×10^6	198	0.106	<1	<1
10	0.5625	14.29	25	170	---	---	73.7	508	27.7×10^6	191	0.103	<1	<1
11	↓	↓	29	200	77.6	535	81.8	564	28.0	193	.102	<1	<1
12	↓	↓	26	180	78.3	540	82.9	572	28.7	198	.102	<1	<1
13	↓	↓	32	220	---	---	82.9	572	29.3	202	.100	<1	<1
14	↓	↓	30	210	80.4	554	85.0	586	29.2	201	.105	<1	<1
Average			28	200	78.8	543	81.3	561	28.6×10^6	197	0.102	<1	<1
15	0.6875	17.46	23	160	81.9	565	85.8	592	28.5×10^6	197	0.102	<1	1
16	↓	↓	29	200	82.6	570	87.9	606	28.8	199	.110	<1	<1
17	↓	↓	26	180	80.8	557	85.7	591	29.2	201	.106	<1	1
18	↓	↓	24	170	79.9	551	82.9	572	29.4	203	.110	<1	<1
Average			26	180	81.3	561	85.6	590	29.0×10^6	200	0.107	<1	<1

TABLE VI.- RESULTS OF ROOM-TEMPERATURE TENSILE TESTS ON

EXTRUDED Be-38Al ALLOY TUBING – Concluded

[0.020-inch (0.508-mm) nominal wall thickness]

(b) Annealed

Specimen	D_n		σ_{tp}		σ_{ty}		σ_{tu}		E		μ_{tp}	e_u	e
	in.	mm	ksi	MN/m^2	ksi	MN/m^2	ksi	MN/m^2	psi	GN/m^2			
1	0.2500	6.35	15	100	46.7	322	50.5	348	27.6×10^6	190	0.122	1	1
2	↓	↓	16	110	47.7	329	58.3	402	29.0	200	.119	2	2
3			20	140	56.0	386	61.6	425	29.5	203	.120	4	4
Average			17	120	50.1	346	56.8	392	28.7×10^6	198	0.120	2	2
4	0.4375	11.11	16	110	47.5	328	51.6	356	29.0×10^6	200	0.116	2	2
5	↓	↓	12	83	45.4	313	47.5	328	28.8	199	.114	2	2
6			18	120	58.1	400	61.0	420	29.6	204	.107	2	---
Average			15	100	50.3	347	53.4	368	29.1×10^6	201	0.112	2	2
7	0.5625	14.29	18	120	---	---	57.7	398	29.8×10^6	205	0.112	<1	1
8	↓	↓	16	110	52.8	364	64.1	442	31.3	216	.107	5	8
9			12	83	44.7	308	59.2	408	30.2	208	.112	5	6
Average			15	100	48.8	336	60.3	416	30.4×10^6	210	0.110	4	5
10	0.6875	17.46	12	83	49.4	341	51.0	352	28.2×10^6	194	0.114	<1	1
11	↓	↓	18	120	49.0	338	55.6	383	29.2	201	.124	2	2
12			14	97	41.6	287	53.9	372	29.4	203	.118	3	5
13			20	140	57.8	398	57.8	398	30.4	210	.115	1	---
14			17	120	45.3	312	54.2	374	29.4	203	.129	4	---
Average			16	110	48.6	335	54.5	376	29.3×10^6	202	0.120	2	3

TABLE VII.- RESULTS OF ROOM-TEMPERATURE COMPRESSIVE TESTS ON EXTRUDED Be-38Al ALLOY TUBING

[0.020-inch (0.508-mm) nominal wall thickness]

(a) As-extruded

Specimen	D_n		σ_{cp}		σ_{cy}		$\bar{\sigma}_{max}$		E_c		μ_{cp}
	in.	mm	ksi	MN/m^2	ksi	MN/m^2	ksi	MN/m^2	psi	GN/m^2	
1	0.2500	6.35	21	140	70.3	485	72.9	503	28.6×10^6	197	0.126
2	↓	↓	23	160	71.6	494	83.5	576	28.2	194	.089
3			18	120	71.6	494	86.4	596	28.8	199	.188
Average			21	140	71.2	491	80.9	558	28.5×10^6	197	0.134
4	0.4375	11.11	24	170	74.2	512	79.3	547	27.9×10^6	192	0.114
5	↓	↓	20	140	74.6	514	88.8	612	28.6	197	.114
6			26	180	75.4	520	80.4	554	28.6	197	.113
Average			23	160	74.7	515	82.8	571	28.4×10^6	196	0.114
7	0.5625	14.29	20	140	72.5	500	85.8	592	28.4×10^6	196	0.112
8	↓	↓	26	180	77.9	537	90.1	621	28.0	193	.112
9			27	190	80.2	553	94.3	650	28.9	199	.110
Average			24	170	76.9	530	90.1	621	28.4×10^6	196	0.111
10	0.6875	17.46	26	180	79.6	549	92.6	638	28.8×10^6	199	0.116
11	↓	↓	22	150	78.6	542	92.4	637	29.0	200	.114
12			25	170	75.8	523	87.7	605	28.5	197	.116
Average			24	170	78.0	538	90.9	627	28.8×10^6	199	0.115

TABLE VII.- RESULTS OF ROOM-TEMPERATURE COMPRESSIVE TESTS ON EXTRUDED Be-38Al ALLOY TUBING – Concluded

[0.020-inch (0.508-mm) nominal wall thickness]

(b) Annealed

Specimen	D_n		σ_{cp}		σ_{cy}		$\bar{\sigma}_{max}$		E_c		μ_{cp}
	in.	mm	ksi	MN/m^2	ksi	MN/m^2	ksi	MN/m^2	psi	GN/m^2	
1	0.2500	6.35	22	150	66.0	455	76.6	528	29.4×10^6	203	0.143
2	↓	↓	16	110	49.6	342	58.9	406	28.0	193	.098
3	↓	↓	20	140	51.6	356	65.8	454	28.2	194	.081
Average			19	130	55.7	384	67.1	463	28.5×10^6	197	0.107
4	0.4375	11.11	17	120	44.2	305	56.9	392	28.4×10^6	196	0.121
5	↓	↓	22	150	60.2	414	69.7	481	28.6	197	.115
6	↓	↓	12	83	41.5	286	58.4	403	28.8	199	.106
Average			17	120	48.6	335	61.7	425	28.6×10^6	197	0.114
7	0.5625	14.29	17	120	43.6	301	55.5	383	28.8×10^6	199	0.126
8	↓	↓	14	97	43.6	301	52.1	359	28.0	193	.116
9	↓	↓	17	120	44.1	304	49.4	341	27.7	191	.119
Average			16	110	43.8	302	52.3	361	28.2×10^6	194	0.120
10	0.6875	17.46	14	97	43.2	298	54.6	376	28.0×10^6	193	0.118
11	↓	↓	16	110	42.4	292	54.7	377	28.4	196	.110
12	↓	↓	16	110	44.6	308	56.0	386	28.0	193	.124
Average			15	100	43.4	299	55.1	380	28.1×10^6	194	0.117

TABLE VIII.- RESULTS OF ROOM-TEMPERATURE COLUMN TESTS ON EXTRUDED Be-38Al ALLOY TUBING

[0.020-inch (0.508-mm) nominal wall thickness]

Specimen	L		D_n		$\frac{L_e}{\rho}$	E_c		$\bar{\sigma}_{max}$		σ_{cr}		$\frac{\bar{\sigma}_{max}}{\sigma_{cr}}$
	in.	mm	in.	mm		psi	GN/m^2	ksi	MN/m^2	ksi	MN/m^2	
As-extruded												
1	3.00	76.2	0.2500	6.35	18.5	27.9×10^6	192	78.3	540	82.6	570	0.95
2	3.00	76.2			18.5	27.7	191	80.2	553	82.6	570	.97
3	6.97	177.0			43.0	28.0	193	58.4	403	62.3	430	.94
4	6.97	177.0			42.8	29.5	203	58.4	403	62.0	427	.94
5	16.00	406.4			98.9	29.0	200	25.4	175	26.0	179	.98
6	16.00	406.4			98.2	28.8	198	23.2	160	26.4	182	.88
7	30.00	762.0			182.7	30.0	207	8.0	55	8.5	59	.94
8	30.00	762.0			184.4	29.0	200	7.8	54	8.3	57	.93
9	3.00	76.2	0.4375	11.11	10.2	28.2	194	90.8	626	89.0	614	1.02
10	3.00	76.2			10.2	27.1	187	83.7	577	89.0	614	.94
11	8.00	203.2			27.0	27.2	188	72.9	503	75.5	520	.97
12	8.00	203.2			27.0	26.2	181	72.1	497	75.5	520	.95
13	30.00	762.0			101.6	29.0	200	24.2	167	25.1	173	.97
14	30.00	762.0			102.0	29.4	203	25.4	175	25.0	172	1.02
15	8.00	203.2	0.5625	14.29	20.9	27.8	192	80.1	552	80.6	556	.99
16	8.00	203.2			20.9	27.0	186	78.3	540	80.5	555	.97
17	25.55	649.0			66.8	29.2	201	43.5	300	43.6	301	1.00
18	25.55	649.0			66.6	28.6	197	43.9	303	43.8	302	1.00
19	8.00	203.2	0.6875	17.46	17.0	28.3	195	87.0	600	84.0	579	1.04
20	8.00	203.2			17.0	28.0	193	86.0	593	84.0	579	1.02
21	27.83	706.9			58.8	29.9	206	48.7	336	49.1	338	.99
22	27.83	706.9			58.9	30.3	209	54.5	376	49.1	338	1.11
Annealed												
1	8.00	203.2	0.2500	6.35	49.1	---------	---	45.3	312	38.0	262	1.19
2	8.00	203.2	.2500	6.35	49.1	---------	---	39.0	269	38.0	262	1.03
3	8.00	203.2	.4375	11.11	27.2	---------	---	47.4	327	47.2	325	1.00
4	8.00	203.2	.6875	17.46	17.0	---------	---	56.8	392	52.5	362	1.08
5	8.00	203.2	.6875	17.46	17.0	---------	---	47.3	326	52.5	362	.90

TABLE IX.- PROPERTIES OF MATERIALS USED FOR COLUMN-EFFICIENCY COMPARISONS

Material	ω		E_c		σ_{cy}	
	lbm/in^3	Mg/m^3	ksi	GN/m^2	ksi	MN/m^2
Aluminum (7075-T6) . . .	0.101	2.80	10 500	72	71	493
Beryllium	.067	1.85	40 000	276	42	290
Be-38Al (as-ext.)	.075	2.08	28 500	197	75	517
Be-38Al (ann.)	.075	2.08	28 500	197	45	310

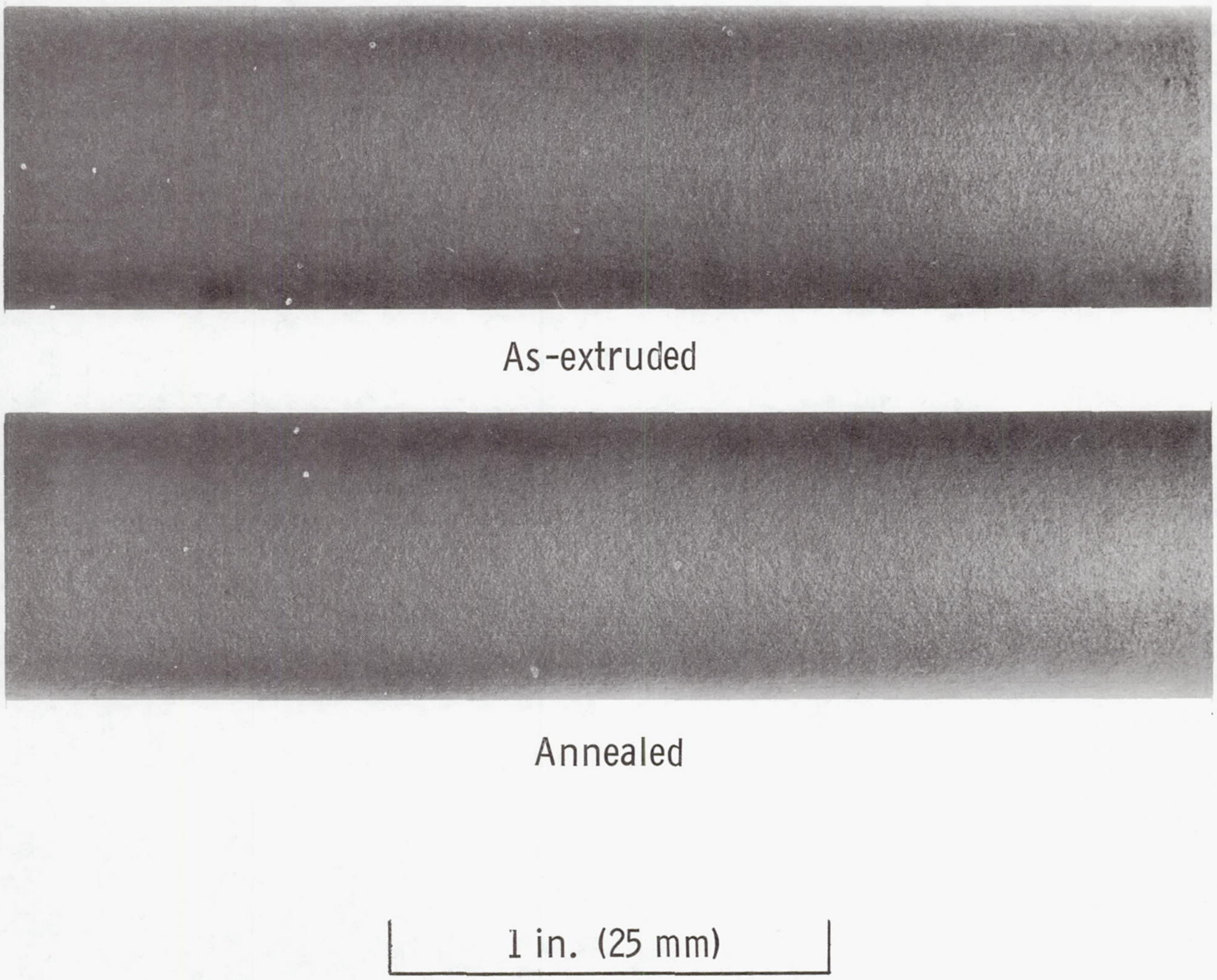
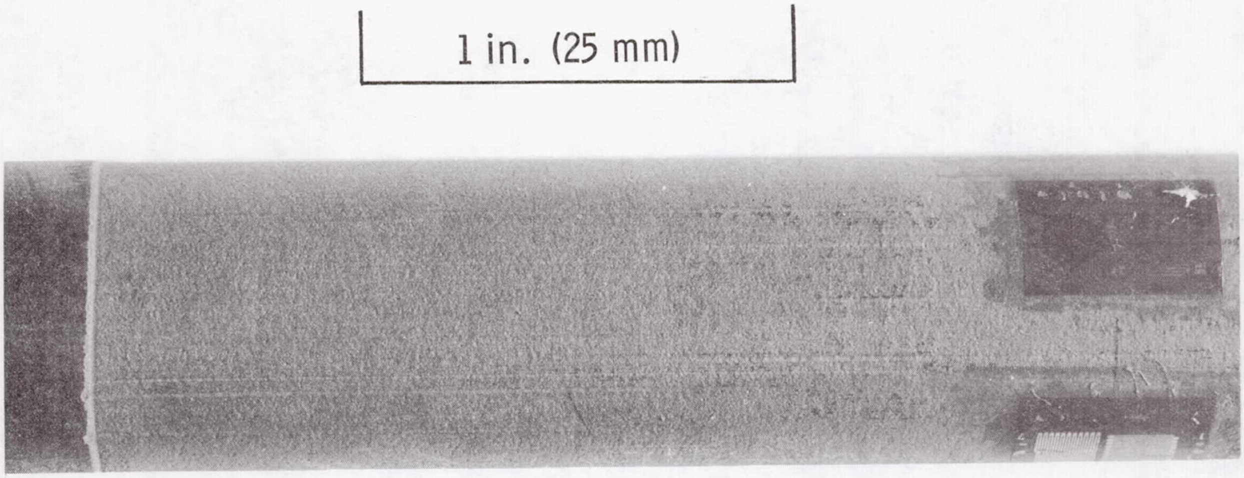
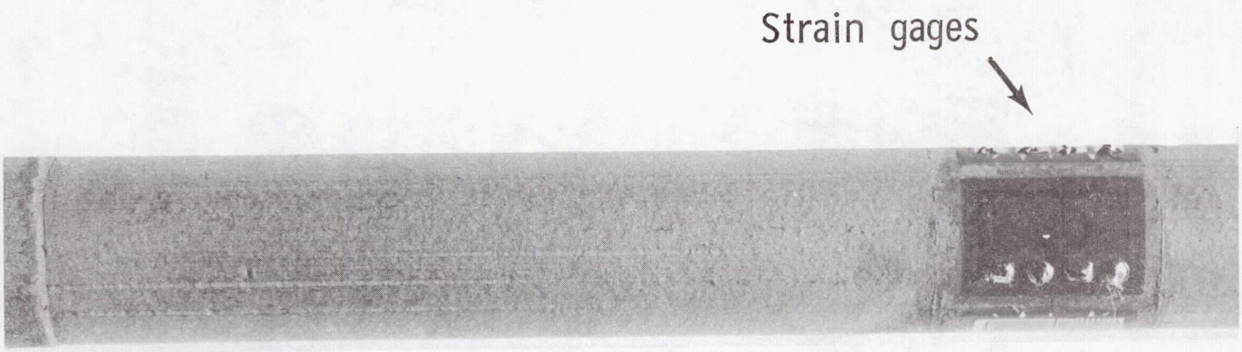


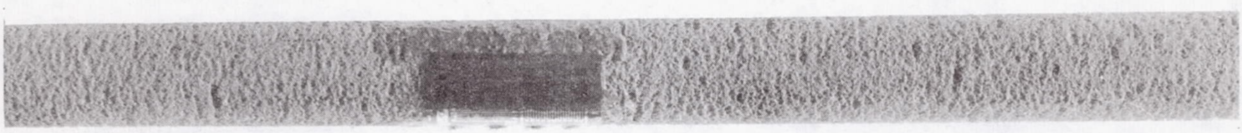
Figure 1.- Typical macrostructure of extruded Be-38Al alloy tubing. L-69-1209



(a) As-extruded.

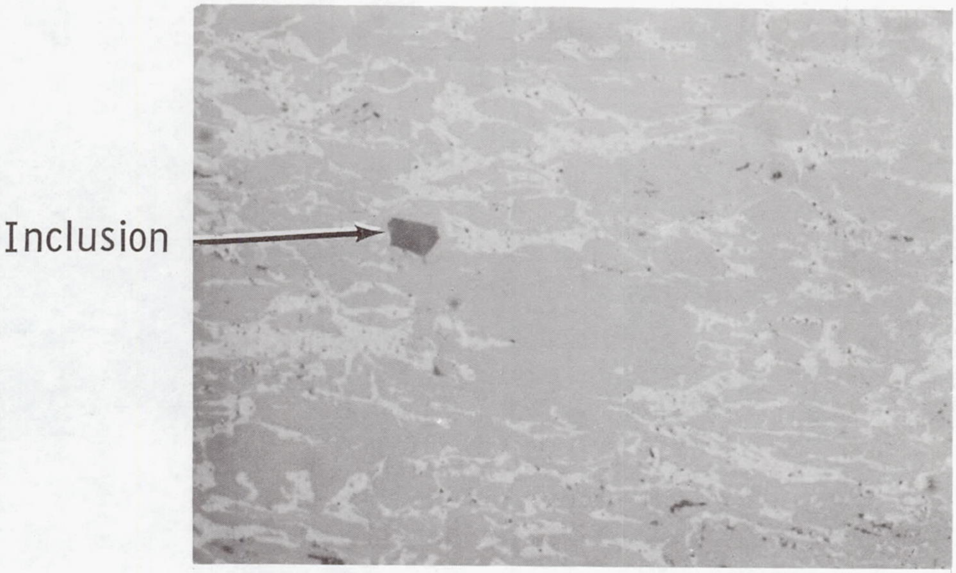


(b) Annealed.

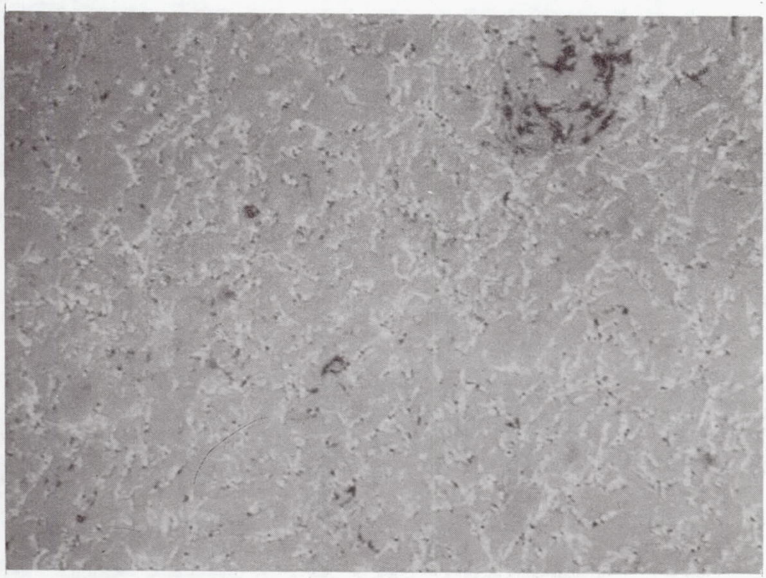


(c) As-extruded, 0.250-inch (6.35-mm) diameter.

Figure 2.- Surface defects on extruded Be-38Al alloy tubing after etching. L-69-1210



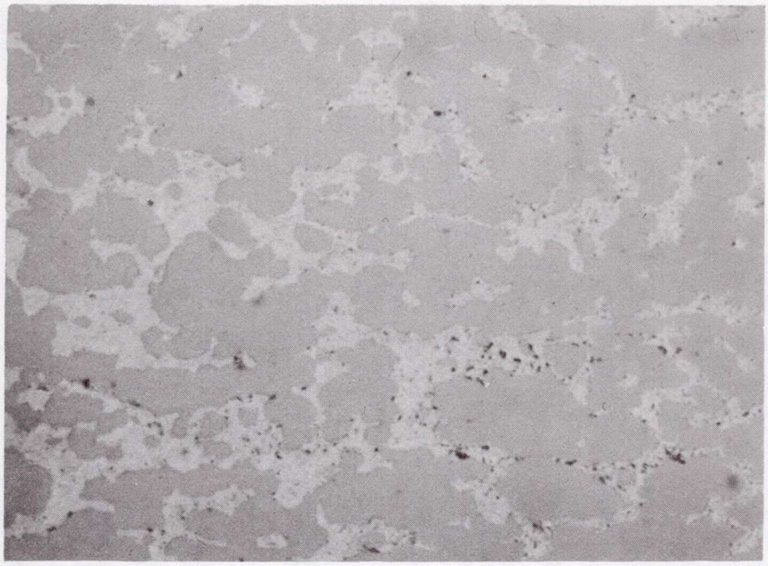
(a) Longitudinal.



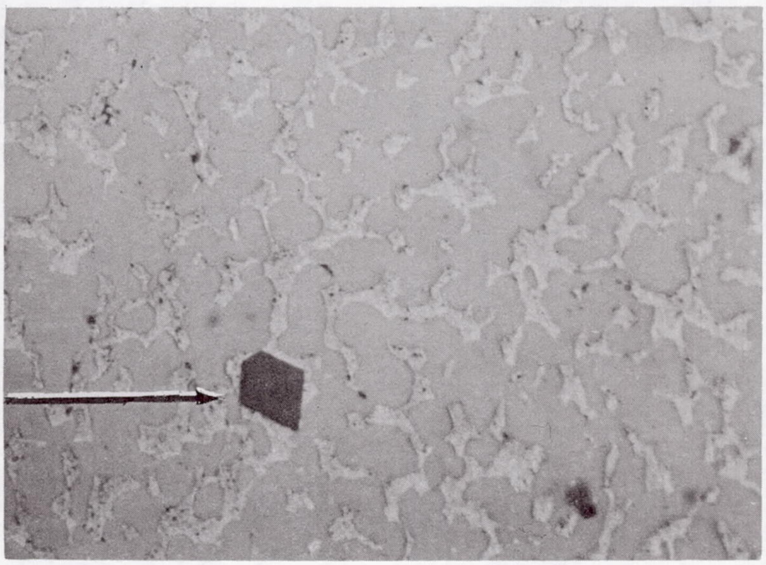
(b) Transverse.

L-69-1211

Figure 3.- Typical microstructure of extruded Be-38Al alloy tubing in the as-extruded condition. Unetched; × 1000.



(a) Longitudinal.



(b) Transverse.

L-69-1212

Figure 4.- Typical microstructure of extruded Be-38Al alloy tubing in the annealed condition. Unetched; × 1000.

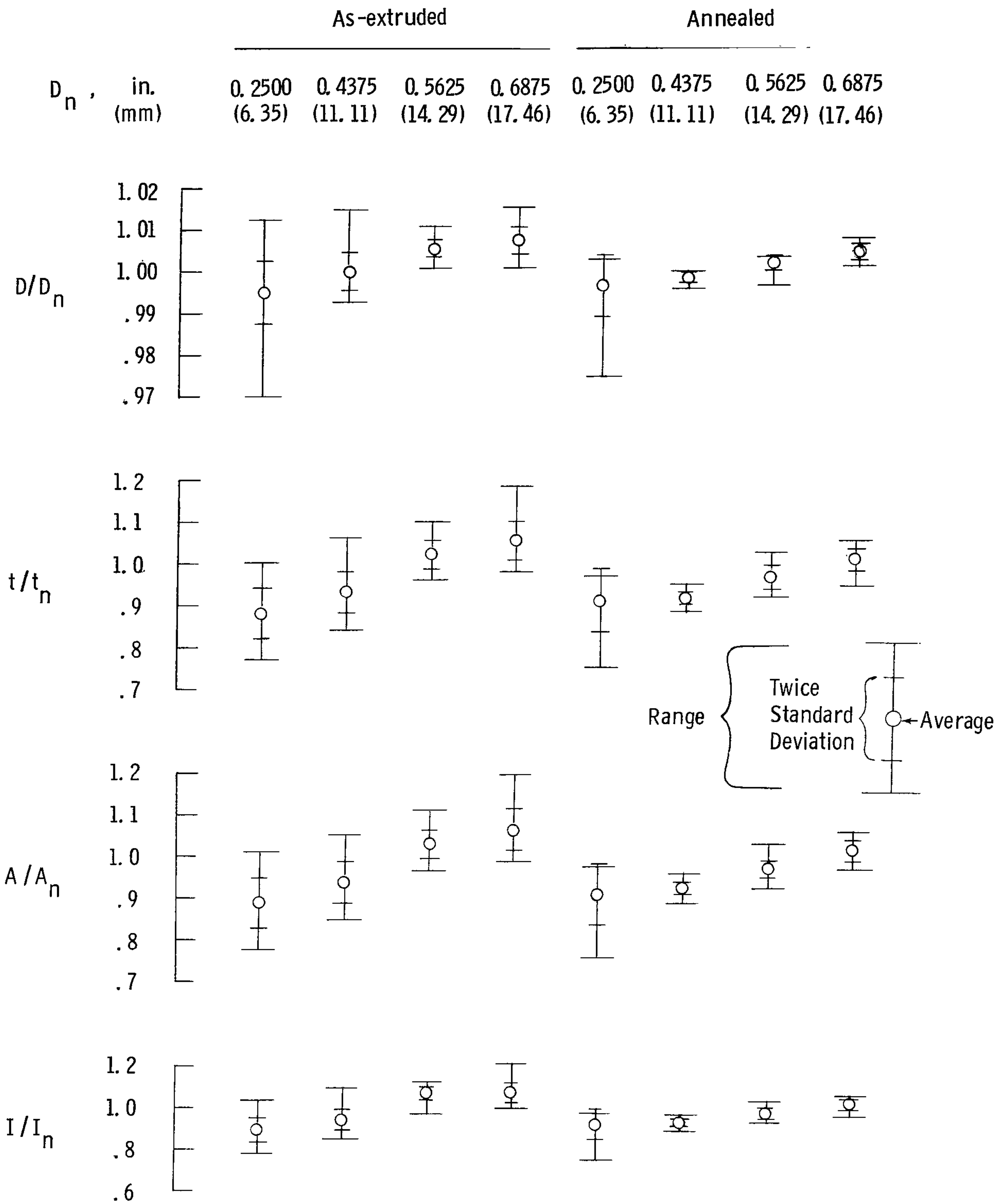


Figure 5.- Normalized dimensional variation of extruded Be-38Al alloy tubing.

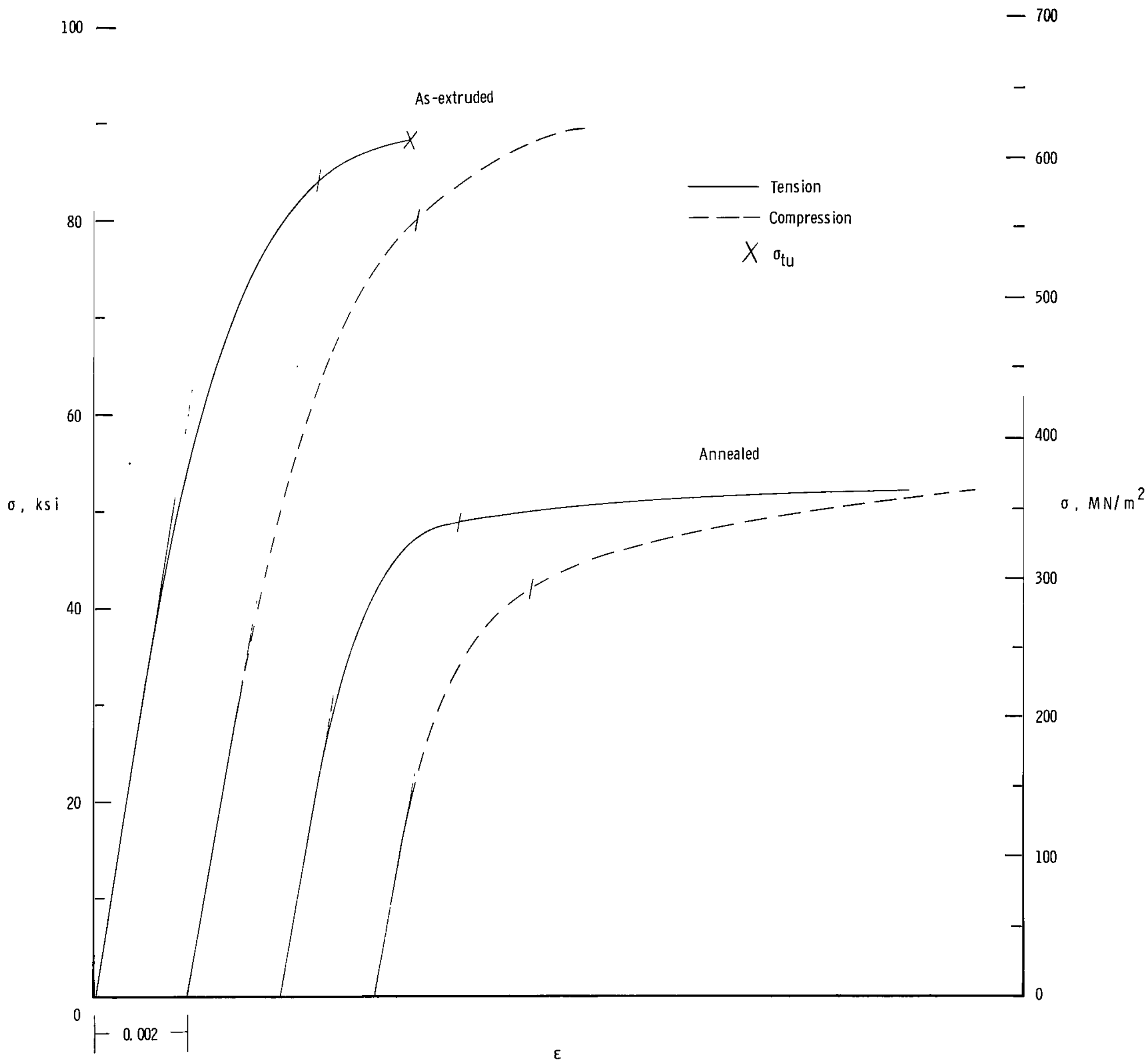


Figure 6.- Typical stress-strain curves for 0.6875-inch-diameter (17.46-mm) extruded Be-38Al alloy tubing.

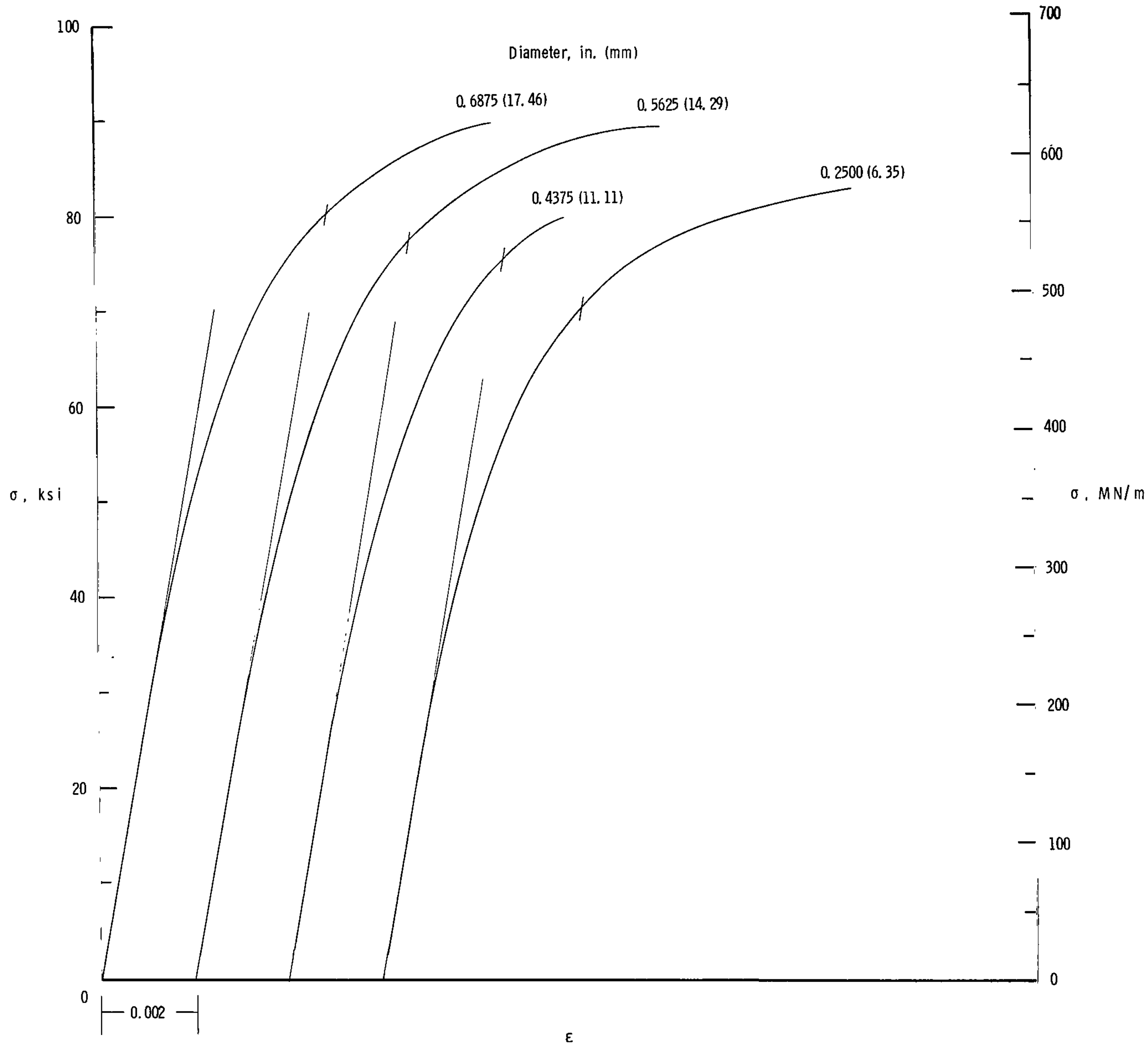


Figure 7.- Typical compression stress-strain curves for extruded Be-38Al alloy tubing in the as-extruded condition.

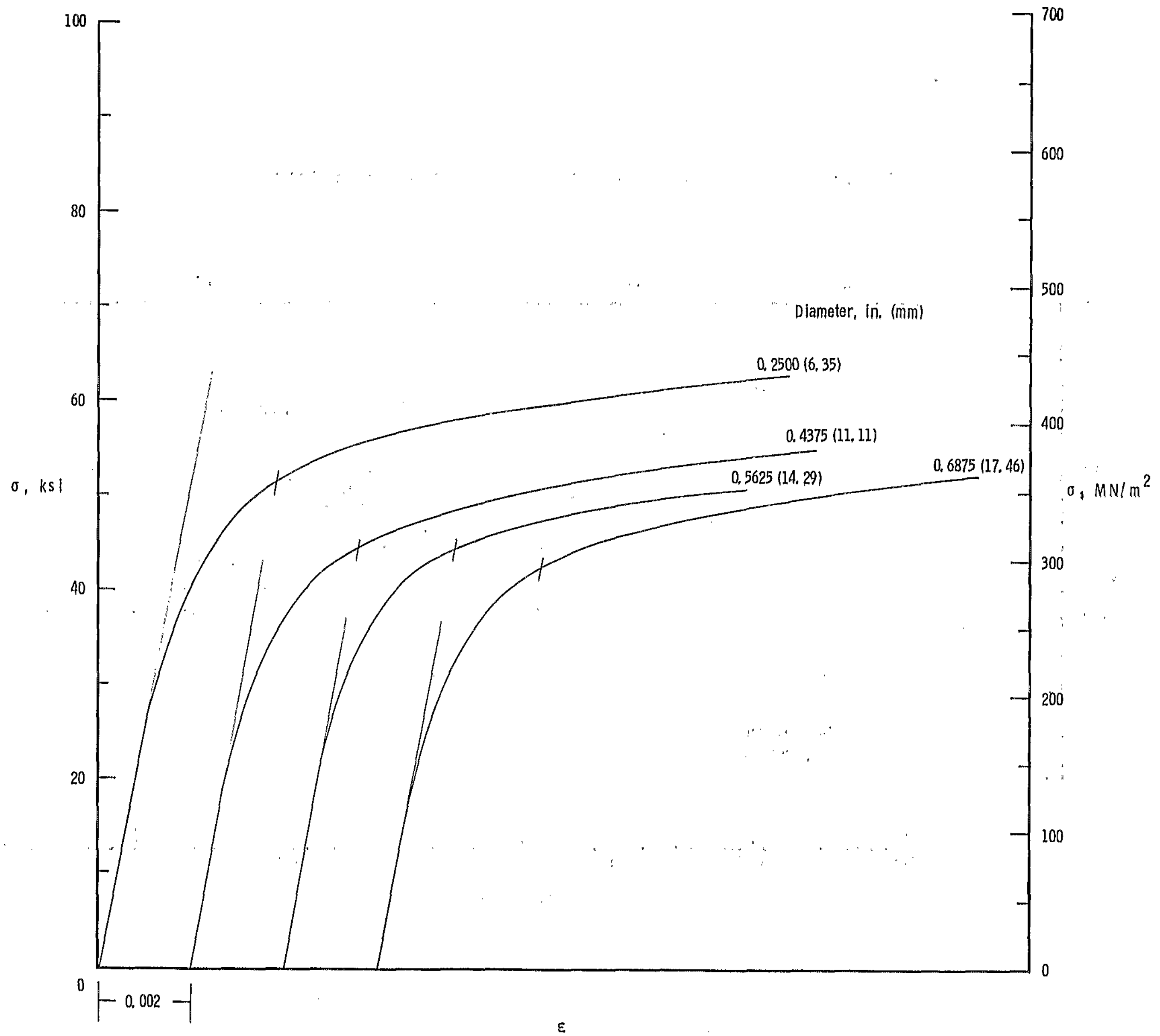


Figure 8.- Typical compression stress-strain curves for extruded Be-38Al alloy tubing in the annealed condition.

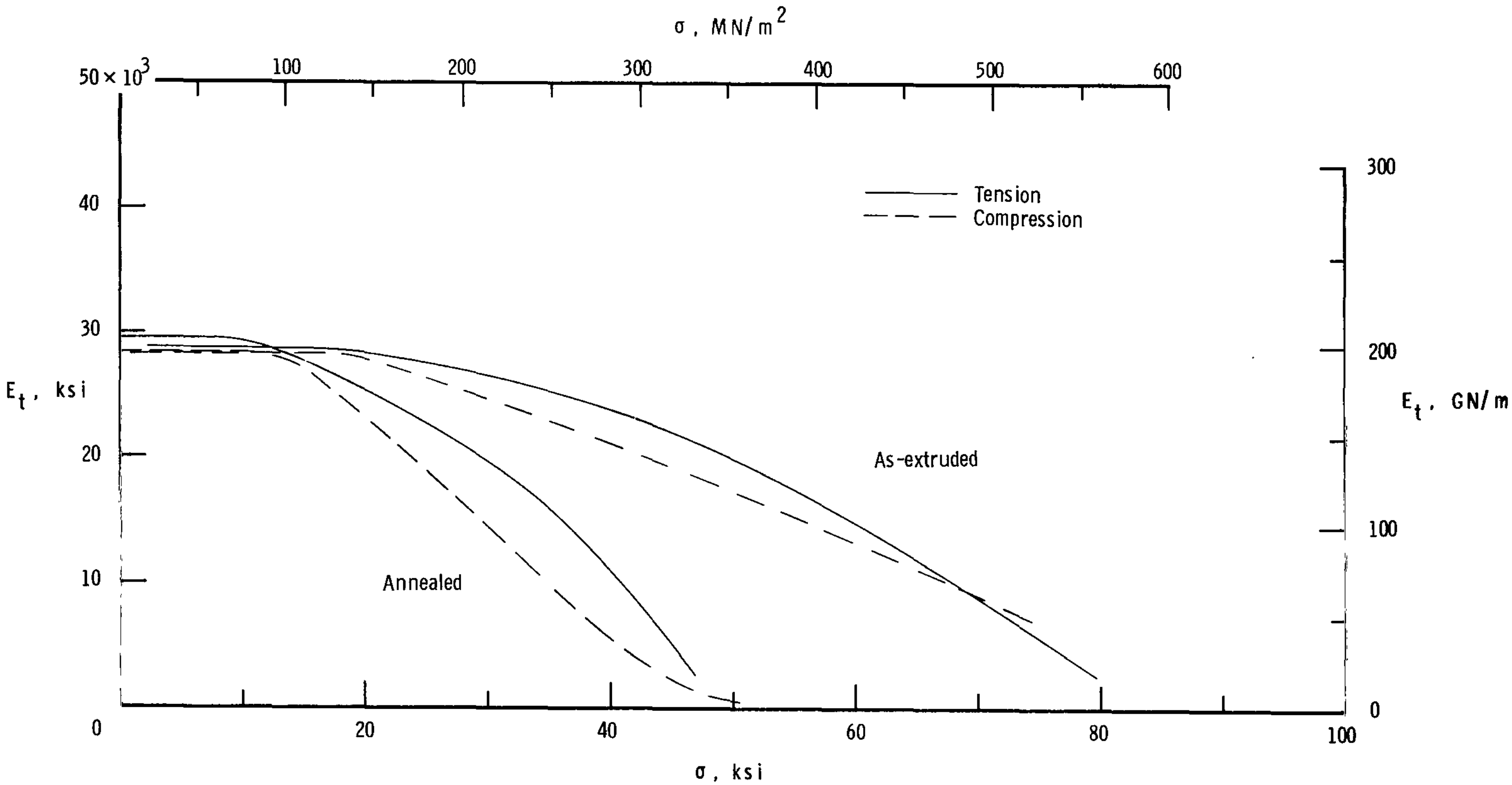


Figure 9.- Variation of tangent modulus as a function of stress for typical extruded Be-38Al alloy tubing.

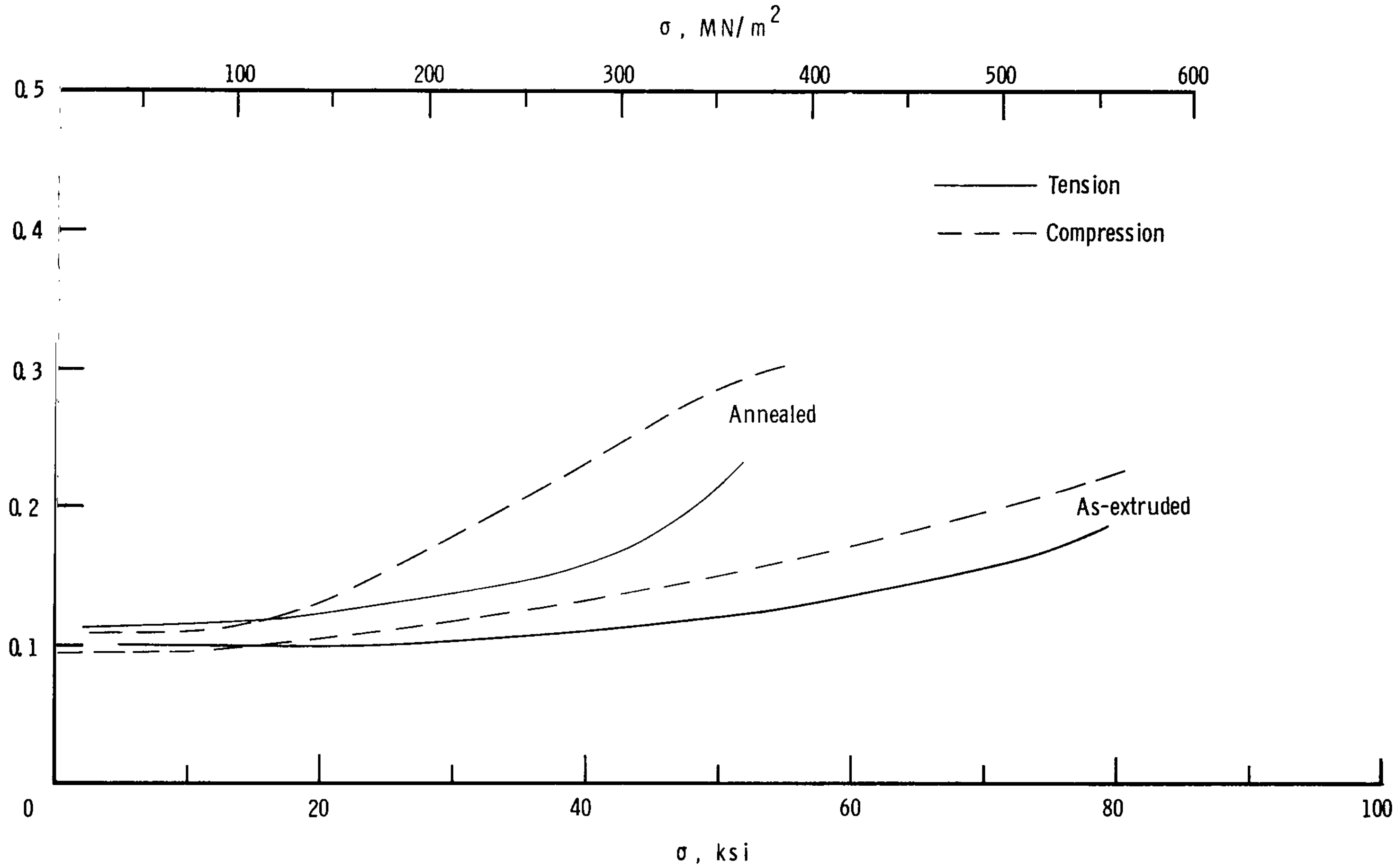


Figure 10.- Variation of Poisson's ratio as a function of stress for typical extruded Be-38Al alloy tubing.

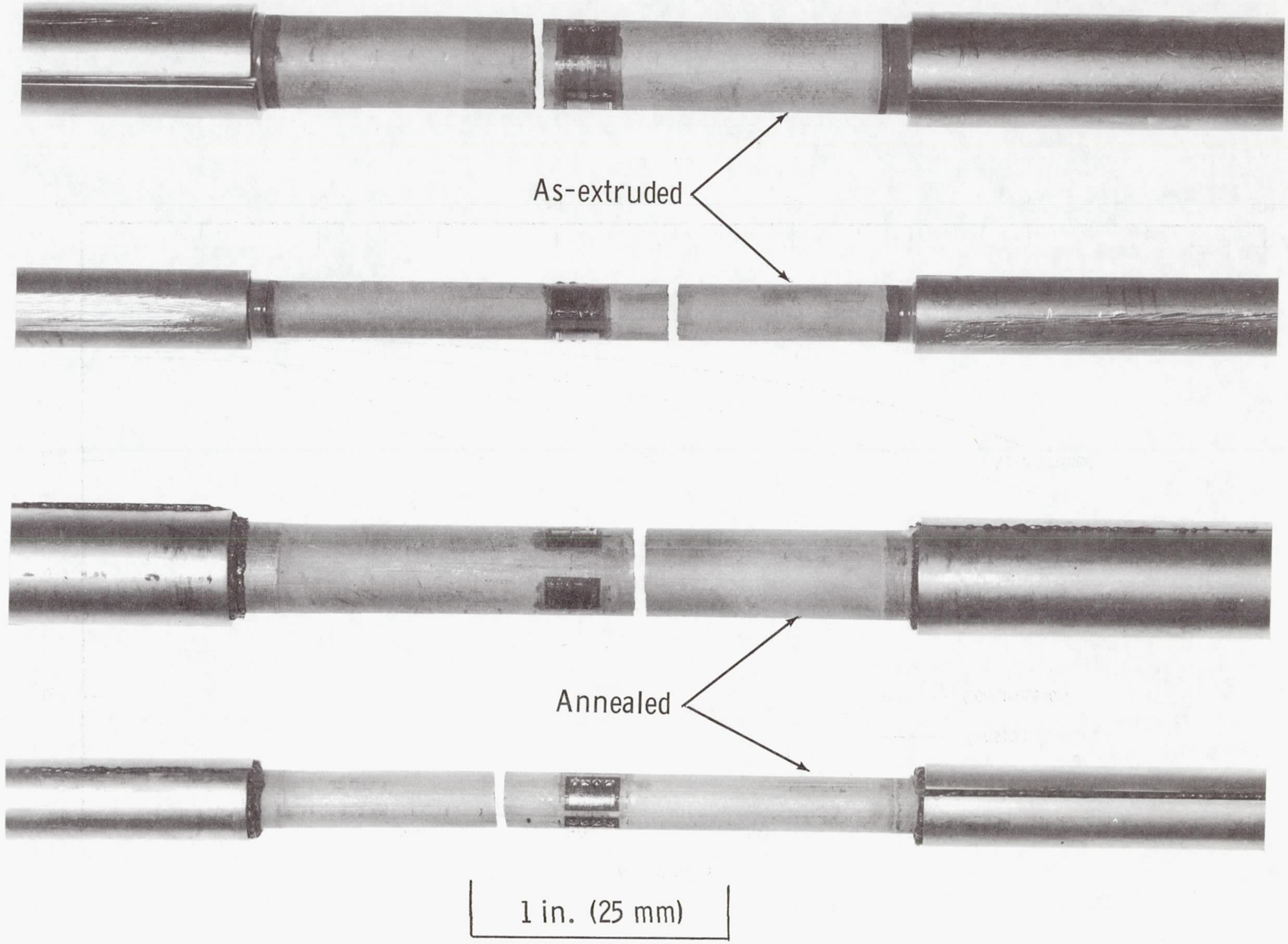
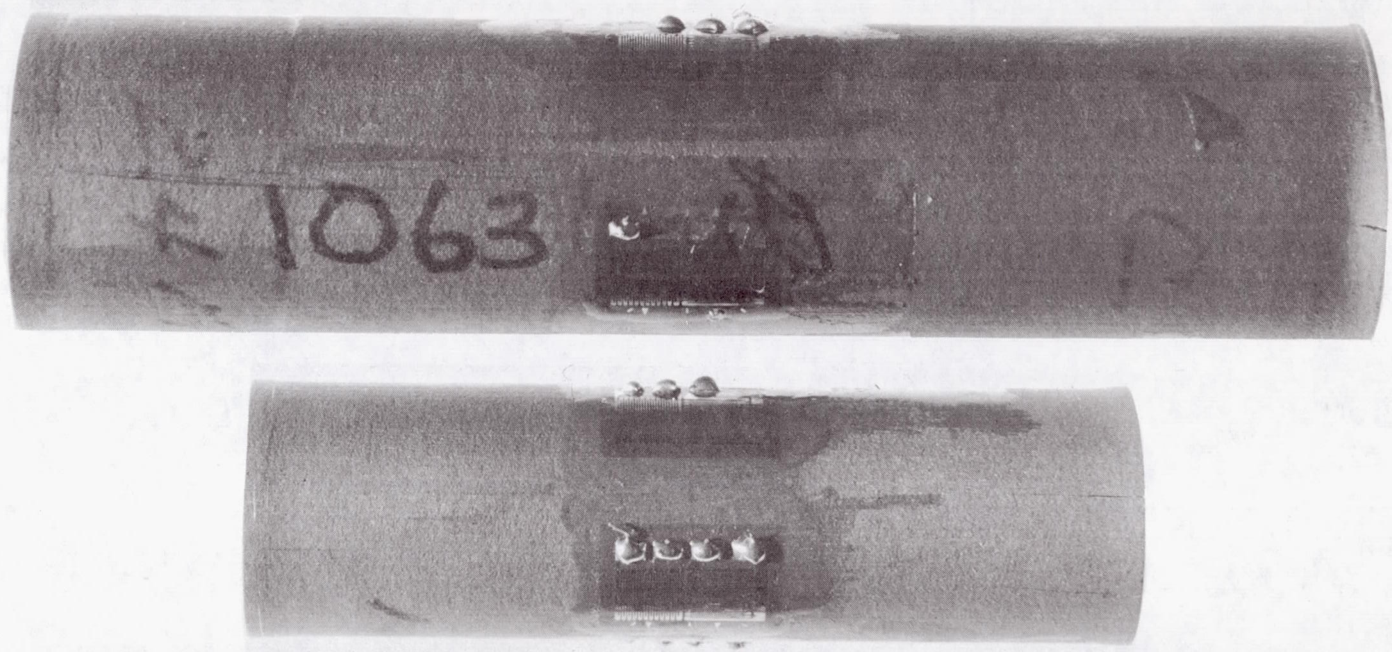


Figure 11.- Typical tensile fracture modes of extruded Be-38Al alloy tubing.

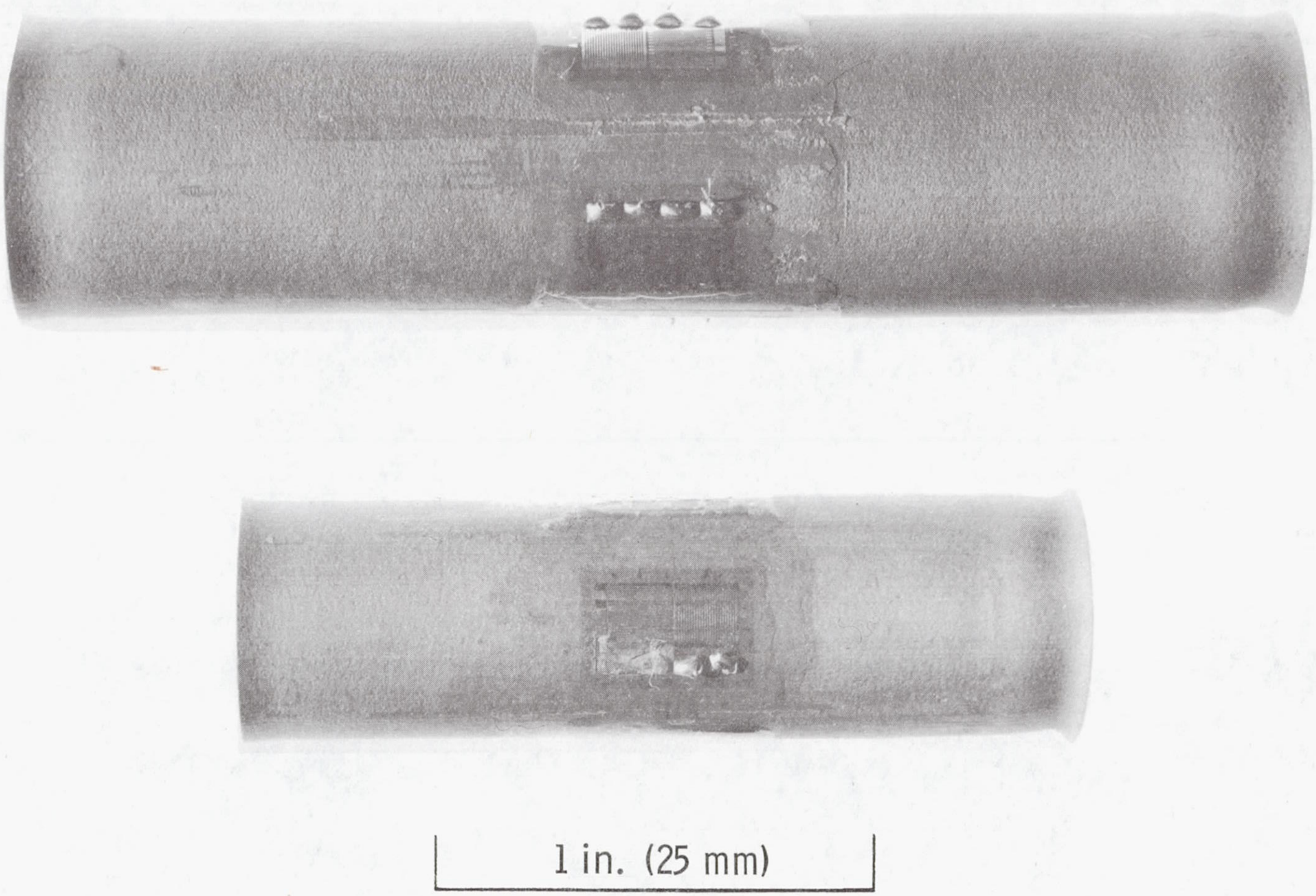
L-69-1213



1 in. (25 mm)

(a) As-extruded.

Figure 12.- Typical compressive failure modes of extruded Be-38Al alloy tubing. L-69-1214



(b) Annealed.

Figure 12.- Concluded.

L-69-1215

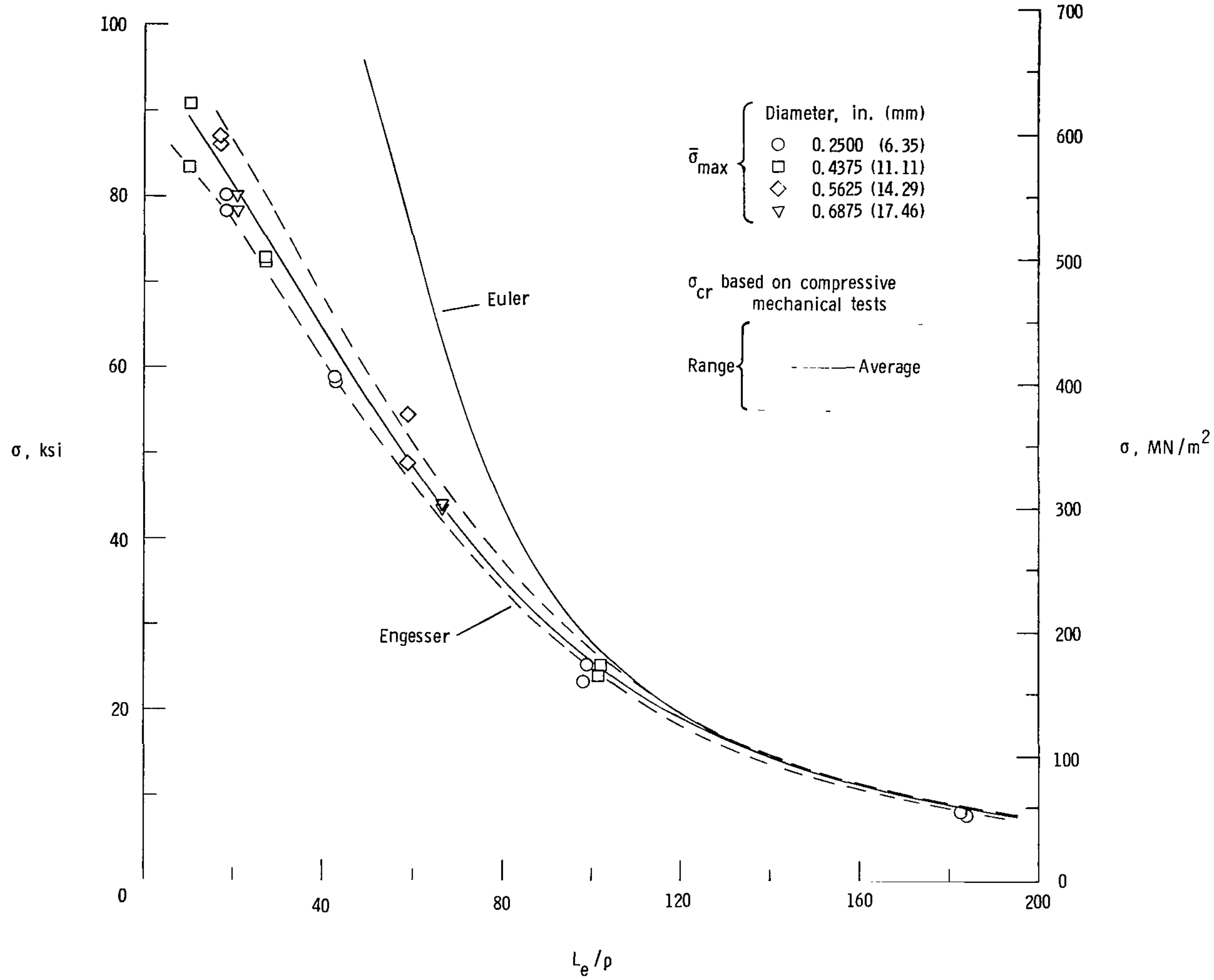


Figure 13.- Column behavior of extruded Be-38Al alloy tube columns in the as-extruded condition.

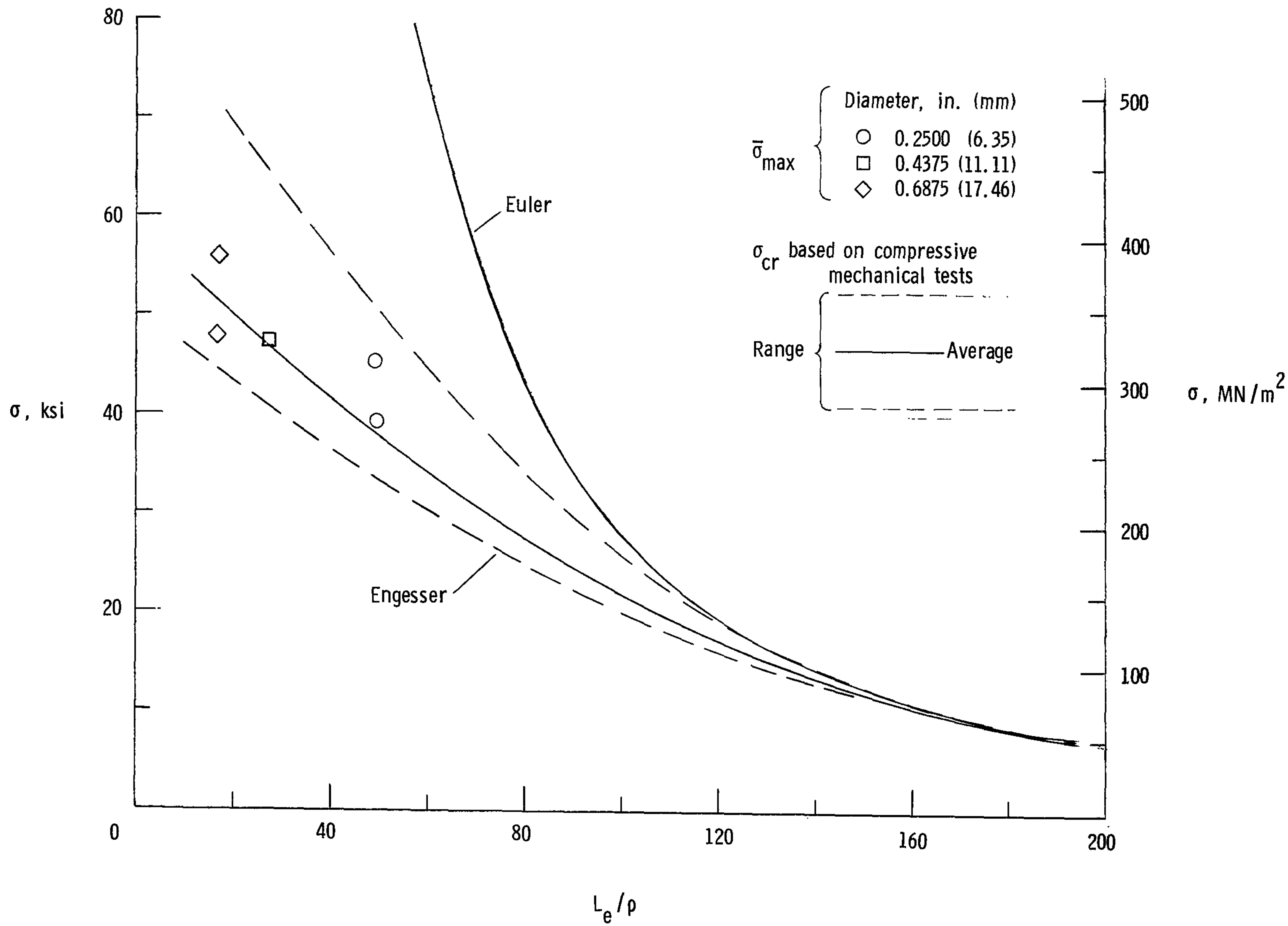


Figure 14.- Column behavior of extruded Be-38Al alloy tube columns in the annealed condition.

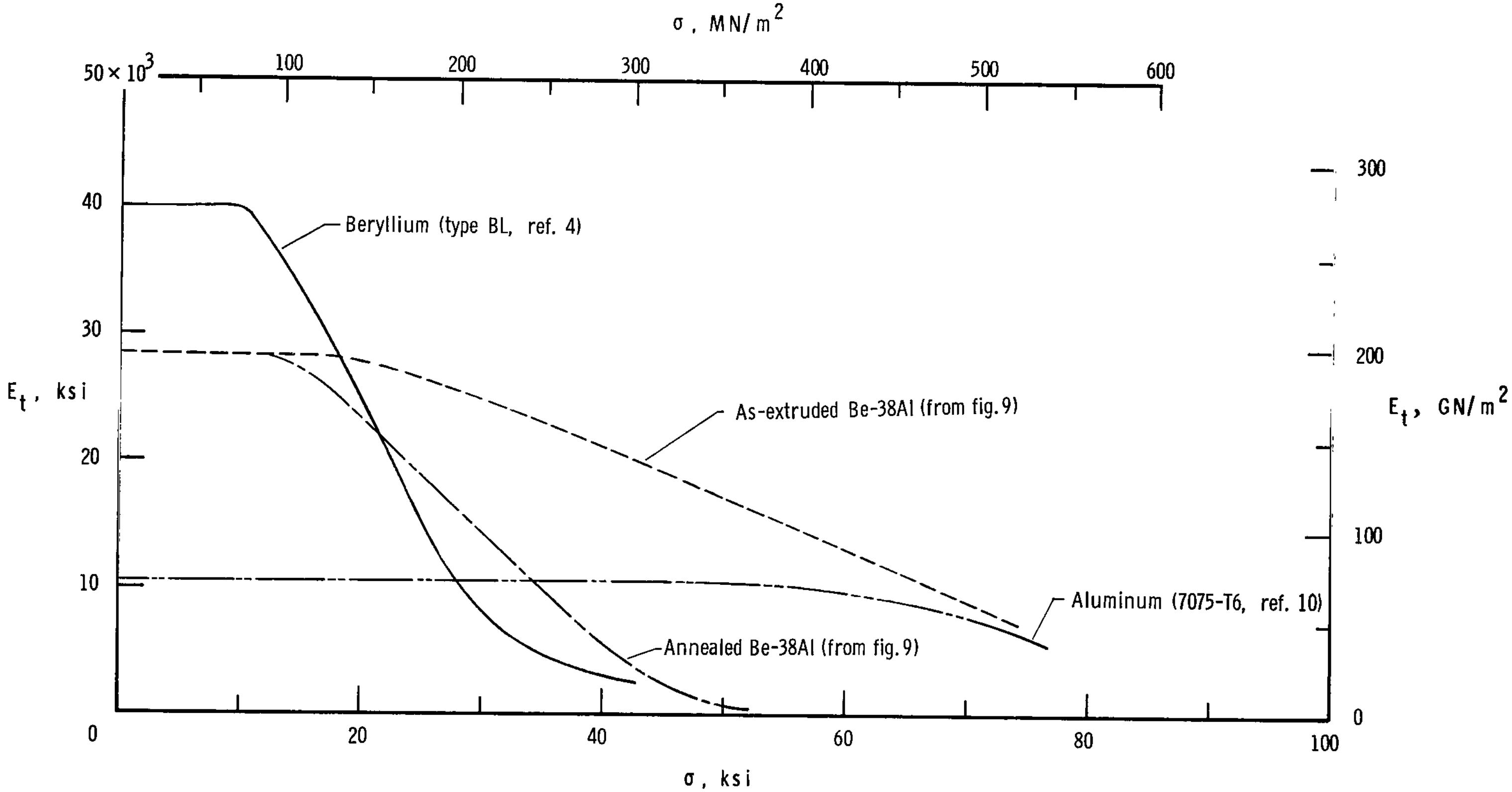


Figure 15.- Compressive tangent-modulus curves for selected materials.

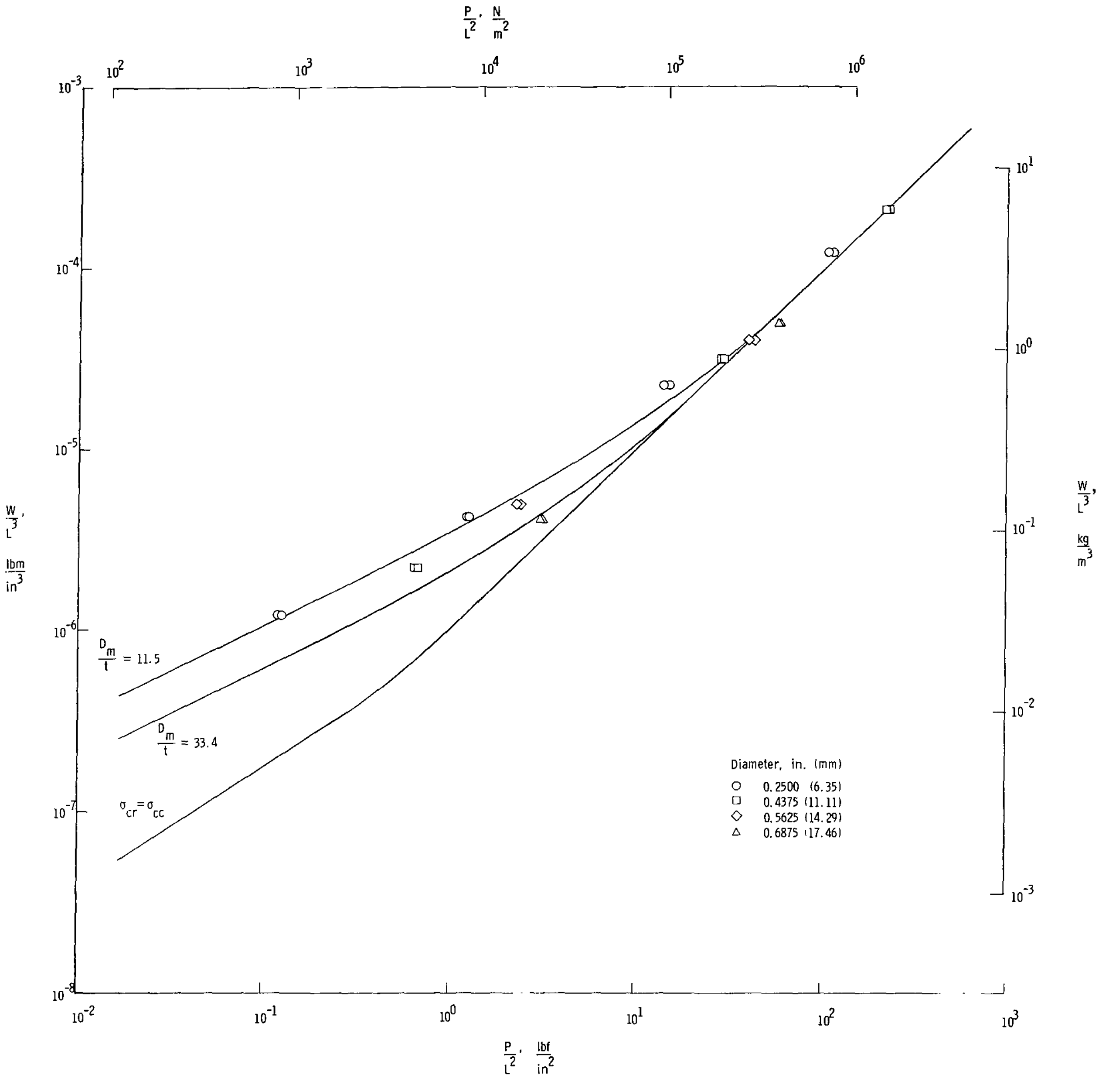


Figure 16.- Mass-strength comparison of experimental and calculated column results for extruded Be-38Al alloy tubing in the as-extruded condition. $c = 4.0$; $k = 0.6$.

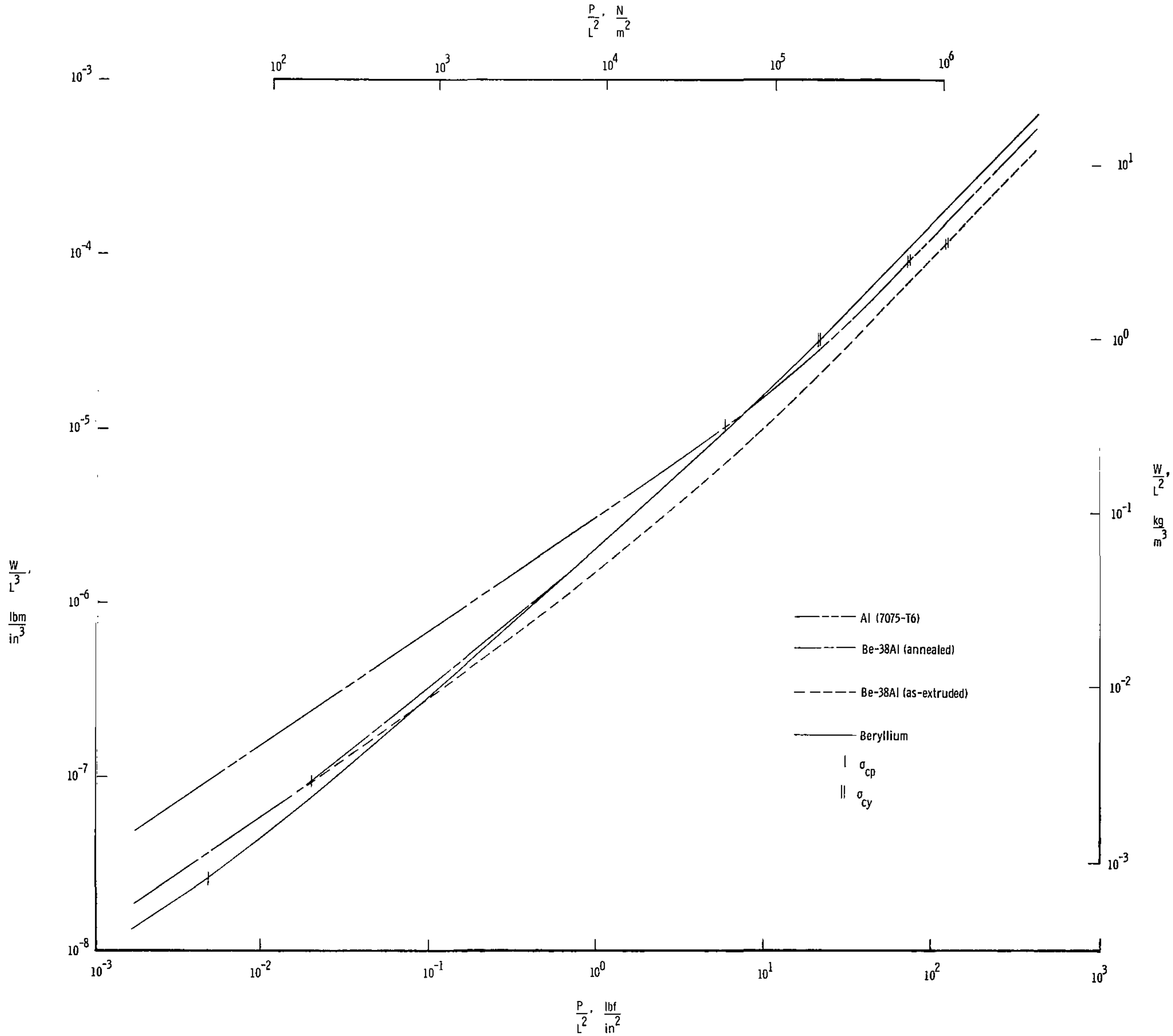


Figure 17.- Efficiencies of minimum-mass round-tube columns for selected materials. $c = 1.0$; $k = 0.6$.

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