CHARACTERIZATION OF BERYLLIUM STRUCTURAL GRADE

TM-778 / S-20OF
by Warren J. Haws
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ABSTRACT

The properties of beryllium structural grade S-200F differ from grade S-200E in its increased strength and ductility. S-200F beryllium offers a 35 ksi 0.2% yield strength, 47 ksi ultimate tensile strength, and a 2% elongation as compared to 30 ksi, 40 ksi, and 1% respectively for S-200E. The major process difference is the use of impact grinding rather than attritioning to produce the input powder. Since S-200F has only recently been made available to users, little design data exists on this grade.

Vacuum hot-pressed S-200F was characterized by mechanical and physical testing, including room and elevated tensile, precision elastic limit, thermal expansion, hardness, torsion, compressive, and notched tensile tests. Fatigue and notched fatigue testing is in progress but not complete at this time. The properties of S-200F and S-200E are compared.

INTRODUCTION

Beryllium grade S-200E was the most common structural grade for over a decade. The powder for this product was made by attritioning which resulted in flat, flakelike particles. These particles were oriented because particle fracture during grinding occurred predominantly on the basal hexagonal close-packed plane, and the flat surfaces correspond to this plane. This orientation effect and the anisotropic nature of the hexagonal beryllium crystal resulted in minimum tensile properties of 40 ksi ultimate tensile strength, 30 ksi 0.2% yield strength, and 1% elongation.

Early in 1984, an improved beryllium structural grade was introduced, S-200F. The minimum tensile properties of this material are 47 ksi ultimate tensile strength, 35 ksi 0.2% offset yield strength, and 2% elongation.

These improvements were made possible by converting the powder making process to impact grinding. Impact grinding causes very rapid fracture and is cryogenic, which promotes fracture along planes other than the basal plane. This produces a blocky particle which has a lower tendency for preferred orientation during consolidation. By reducing the degree of preferred orientation, anisotropy is reduced. Hence, the minimum values of the tensile properties are improved.

The S-200 grades of beryllium have become widely accepted and used for a diverse number of applications over the years. Some typical applications include inertial guidance systems, missile interstages, spacecraft structures, and small rocket nozzles. The purpose of this study was to characterize the physical and mechanical properties of the improved S-200F material so that designers can make optimum use of this material. The properties measured include tensile properties at room and elevated temperatures (ultimate tensile strength, 0.2% yield strength, upper yield strength, lower yield point, percent elongation and percent reduction in area), precision elastic limit (also Young's modulus and 0.01% offset yield strength), coefficient of thermal expansion between 5 C and 65 C, hardness, shear modulus, compressive strength, and notched tensile strength. Fatigue and notched fatigue properties are being measured but testing is not complete at this time. Thermal expansion to 1200 F and fracture toughness tests are also planned.

MATERION BRUSH BERYLLIUM & COMPOSITES
14710 W Portage River South Rd
Elmore, OH 43416-9502
phone: 419.862.4533 or 419.862.4171 Intl: 419.862.4127
e: berylliumandcomposites@materion.com

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MATERIALS AND PROCEDURE

Specimen Preparation

The specimens for this characterization were machined from a 5 in. diameter core taken out of a 17-3/4 in. diameter by 64-3/8 in. long vacuum hot-pressed billet. The lot number of the vacuum hot pressing was 3001. The results of the chemical analysis of this pressing are shown in Table 1. The S-200E and S-200F specification values are included for comparison. Mechanical property test

specimens were taken parallel to the axis of the hot pressing (longitudinal direction) and perpendicular to the axis of the hot pressing (transverse direction). Most tests were conducted in triplicate. Exceptions to this will be noted. All specimens were inspected for cracks and checked visually for obvious discontinuities. The specimens were etched in an aqueous solution of 2% HF-2% H_2SO_4-2% HNO_3 by volume to remove machining damage (0.004 in. to 0.0045 in. per surface). All tests were conducted on material in the as-pressed condition.

Specimen Testing

The majority of the testing was performed at the Brush Wellman-Cleveland R & D facility. The thermal expansion was performed by the quality assurance department of Brush Wellman's Elmore, Ohio manufacturing facility. The torsion testing and smooth fatique testing were performed by Metcut, Inc. of Cincinnati, Ohio. The details of the individual tests are described below.

Tensile Testing

The tensile testing at room and elevated temperature conformed to ASTM specifications E8, E4, E21, with the additional requirements specified by the Materials Advisory Board[2]. The specimens were 1/4 in. nominal gage diameter with a 1 in. gage section, with tapered-end grips. An ASTM type B-1 extensometer was used to measure strain. The specimens were tested on an Instron test machine. The elevated temperature tensile specimens were heated using a resistance furnace. Two thermocouples were attached to the specimen, one for control and one for measurement. The properties measured were 0.2% yield strength, upper yield strength, lower yield strength, ultimate tensile strength, percent elongation, and reduction in area.

Precision Elastic Limit

Precision stress-strain experiments were conducted at room temperature according to MAB specifications[2]. The specimens used were the same type used for tensile testing. Precision strain gages (micromeasurement type EA06-260-BF350) were used to measure the strain. An Arcweld creep-rupture test machine was used to apply the dead weight load and remove it. Loads were applied to produce permanent strains up to 100×10^{-6} in./in. The properties measured were the precision elastic limit (stress required to produce 10^{-6} in./in. permanent strain), the 0.01% offset yield strength, and the Young's modulus (chord modulus between the stress at the first applied load and the stress at the last load which gave zero microstrain permanent set ASTM E-111).

Thermal Expansion

Thermal expansion was measured over a temperature range of 5 C to 55 C. A He-Ne laser illuminated Fizeau-type interferometer operated in vacuum was used to measure the thermal expansion (ASTM E-289). The specimen measured

was a cube, 7/8 in. per side with three-point support on each face.

Hardness

Hardness was measured at room temperature on a Wilson Rockwell Hardness Twin Tester. The Rockwell B scale was used for these tests. The experiments were conducted according to ASTM E-18.

Torsion

The shear modulus was measured at room temperature according to ASTM E-143. The specimens used were 1/4 in. di-

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14710 W Portage River South Rd
Elmore, OH 43416-9502
phone: 419.862.4533 or 419.862.4171 Intl: 419.862.4127
e: berylliumandcomposites@materion.com

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ameter rounds. The modulus was determined by the secant modulus between the origin and the 16.0 ksi stress level. The slope of the line was determined by a least squares fit to the data. The rupture modulus was determined from the maximum stress from the stress strain curve.

Compressive

Compression testing was performed to measure the compressive yield strength at room temperature and 400 F. The procedure followed ASTM E-9 and ASTM E-209 with the following changes. The specimen had a 1/4 in. diameter with a 1/2 in. gage. The overall length of the specimen including the tapered end was 0.965 in. Due to the short length of the gage section, an extensometer could not be used to measure the strain. The strain was measured by running the crosshead at a constant speed 0.005 in./minute. The yield strength was determined at the 0.2% offset.

Notched Tensile

Notched tensile specimens were tested to evaluate the notch strength ratio. ASTM procedure E-602 was used. The specimen size was the same as the 1/4 in. tensile specimens. The circumferential notch contained a 60° flare and

a root radius of 0.010 in. The notch diameter was nominally 0.173 in. The stress concentration factor (K_t) in tension was approximately three. Specimens were tested at room temperature and 400 F.

Fatique

Smooth fatigue testing was performed according to ASTM specification E-466. The specimens used were 3/8 in. diameter at the grips with a continuous radius between ends and a minimum diameter of approximately 1/4 in. The tests were performed using a rotating beam with cantilever bending with fully reversed bending. A Krouse rotating beam fatigue machine was used.

RESULTS AND DISCUSSION

Tensile Testing

The tensile properties for S-200F Lot 3001 are shown in Table 2. At room temperature, the ultimate tensile strength is 55.4 ±0.3 ksi and 59.1 ±0.7 ksi for the longitudinal and transverse directions respectively. These values are typical of production S-200F material. The average ultimate strength of 22 specimens from 7 different vacuum hot-pressed lots (6 different powder lots) is 55.9 ±2.1 ksi and 59.6 ±2.4 ksi for the longitudinal and transverse directions respectively.

The ultimate tensile strength is higher in the transverse direction than the longitudinal direction for S-200F. The magnitude of the difference between these two directions is about half the difference observed for S-200E. Above 400 F in S-200F the degree of anisotropy is significantly reduced. The comparison with S-200E is shown graphically in Figure 1. At room temperature the minimum value for the ultimate strength of S-200F is about 8 ksi greater than S-200E. However, above 600 F, the tensile strength of S-200F becomes less than that of S-200E. A possible reason for the sharper decline in tensile strength of S-200F compared to S-200E is that S-200F has a finer grain size and less oxide at the grain boundaries.

The 0.2% offset yield strength for Lot 3001 at room temperature is 38.2 ±0.5 ksi and 38.0 ±0.1 ksi for the longitudinal and transverse directions respectively. These values are averages of three specimens in each direction of one vacuum hot pressing. The average yield strength of 22 specimens from 7 vacuum hot-pressed lots of S-200F (6 powder lots) is 39.3 ±2.3 ksi and 39.9 ±2.7 ksi respectively for the longitudinal and transverse directions. As with the ultimate strength, the yield strength of S-200F exhibits less anisotropy than S-200E.

The comparison of yield strength in S-200F to S-200E as a function of temperature is shown in Figure 2. At room temperature, the yield strength of S-200F is about 4 ksi greater than S-200E. The yield strength of S-200F decreases as a function of temperature faster than the yield strength of S-200E. The crossover point is about 1000 F.

The tensile elongation for Lot 3001 at room temperature is 3.41 ±0.3% and 6.1 ±0.5% respectively for longitudinal and transverse directions. The average tensile elongation of 22 specimens from 7 vacuum hot-pressed lots is 3.1 ±0.3% and 5.2 ±0.8% respectively. The tensile elongation exhibits considerable anisotropy compared to that exhibited by the ultimate and yield strength.

The comparison of tensile elongation in S-200F to S-200E is shown in Figure 3. For S-200E, only longitudinal data were available. The elongation of S-200F is higher than S-200E at room temperature as well as at elevated temperatures. The elongation increases as a function of temperature until it peaks at about 600-800 F after which it decreases.

Precision Elastic Limit

The average Young's modulus was 45.1 ±1.0 msi and 44.9 ±0.7 msi respectively for the longitudinal and transverse directions. These values are the average of three specimens in each direction taken from the middle section of Lot 3001. The values along with the values for the Precision Elastic Limit and 0.01% offset yield strength are shown in Table 3.

The 0.01% offset yield strength was 27.6 ±0.6 ksi and 29.5 ±0.7 ksi respectively for the longitudinal and transverse directions. The values for the 0.01% offset yield strength were calculated by interpolating the stress versus set strain data from the Precision Elastic Limit data.

The average Precision Elastic Limit was 4.7 ±0.4 ksi and 5.0 ±0.3 ksi respectively for the longitudinal and transverse directions. The stress-strain curves are shown in Figures 2 and 3 for the longitudinal and transverse directions respectively. The stress-permanent strain curves are shown in Figure 4 and Figure 5 respectively.

The data exhibits the typical differences between the longitudinal and transverse properties seen in other impact ground powders. The properties are higher for the transverse direction in S-200F than the longitudinal. The difference between the two directions was less pronounced at lower permanent strains. In the elastic region, there was no significant difference as evidenced by the values for Young's modulus and Precision Elastic Limit.

There is no comparison with S-200E for the Precision Elastic Limit and 0.01% offset yield strength values since these two properties were not commonly measured. The value for Young's modulus compares well with the reported value of 44 msi.

Thermal Expansion

Precision thermal expansion was measured over the nominal temperature range of 5 C to 65 C. The data are shown in Table 4. The average coefficient of thermal expansion for the longitudinal and two transverse directions was

11.39×10^{-6} in/in/C, 11.57×10^{-6} in/in/C, and 11.45×10^{-6} in/in/C, respectively.

These values compare well with values for S-200E. The degree of anisotropy appears to be less in the S-200F material. A possible explanation is that the use of a more equiaxed particle created by impact grinding has decreased the degree of ordered packing during vacuum hot pressing. These conclusions should be viewed with caution since only one specimen from each type of material was available for comparison.

Hardness

The value for the hardness was obtained by taking three readings each on three specimens. The average was obtained by throwing out the highest and lowest value and averaging the remaining values. The Rockwell B hardness was 85.5 ±0.9 and 85.4 ±1.2 for the longitudinal and transverse directions respectively. This is comparable to S-200E.

Torsion

The results of the torsion testing are shown in Table 5. The average shear modulus was determined to be 19.5 ±0.7 msi and 19.4 ±0.4 msi for the longitudinal and transverse directions respectively. These values are essentially the same as those pub-

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14710 W Portage River South Rd
Elmore, OH 43416-9502
phone: 419.862.4533 or 419.862.4171 Intl: 419.862.4127
e: berylliumandcomposites@materion.com

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lished for S-200E. The average shear rupture modulus was determined to be 43.1 ±1.9 ksi and 44.8 ±1.2 ksi for the longitudinal and transverse directions respectively. There are no comparative values for S-200E.

Compressive Yield Strength

The compressive yield strength (0.2% offset) reported is the average of three determinations for each orientation. The compressive yield strength at room temperature was 40.6 ±0.7 ksi and 39.3 ±1.3 ksi for the longitudinal and transverse orientations respectively. Measurements are in progress to obtain data at 400 F.

Notched Tensile Strenqth

A stress concentration factor (K_t) of three was used for the measurements made at room temperature and 400 F. The notch strength and notch strength ratio (NSR) are shown in Table 6. At room temperature, S-200F does

not exhibit any notch sensitivity as shown by the notch strength ratio of approximately one.

At 400 F the notch strength ratio of S-200F increased to 1.21. This means that the notch ultimate tensile strength of beryllium is greater than the unnotched strength at 400 F. This notch strengthening is to be expected since the ductility of the beryllium increases with temperature between room temperature and 400 F. This behavior is basically the same as that is observed for S-200E.

Fatigue

The results of the room temperature smooth fatigue tests are shown in Table 7. The S/N curves for this data are shown in Figures 4 and 5. From these curves the transverse fatigue properties appear to be greater than the longitudinal properties. The fatigue life (10^7 cycles) is 38.0 ksi and 38.5

ksi respectively for the longitudinal and transverse directions.

This fatigue life is based on completely reversed loading where the ratio

of maximum stress to minimum stress (R value) is -1. The fatigue life can be converted to other types of loading (different R values) using Goodman Diagrams. Figures 6 and 7 graphically illustrate the use of the Goodman Diagram in interpolating the current data (R = -1) to an R value of 0.1. The fatigue life for an R value of 0.1 is 46 ksi and 48 ksi respectively for the longitudinal and transverse directions. These values compare to 36 ksi for the same R value in S-200E.

CONCLUSIONS

The following conclusions may be derived from this characterization study of S-200F:

1. The typical room temperature tensile properties of S-200F exceed those of its predecessor S-200E.
2. Anisotropy is reduced in S-200F, but not totally eliminated.
3. Both Young's modulus and the shear modulus remain unchanged between S-200E and S-200F, a result which is expected since these are structure-insensitive properties.

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TABLE 1 - CHEMICAL COMPOSITION OF LOT 3001

	Lot 3001	S-200E Spec(1)	S-200F Spec(1)
Beryllium Assay	99.03%(3)	98.0%(2)	98.5%(2)
Beryllium Oxide	1.06%	2.0%	1.5%
Aluminum	0.03%	0.16%	0.10%
Carbon	0.08%	0.15%	0.15%
Iron	0.08%	0.18%	0.13%
Magnesium	0.02%	0.08%	0.08%
Silicon	0.03%	0.08%	0.06%

(1) Maximum, percent unless otherwise noted
(2) Minimum percent
(3) Calculated

TABLE 2 - TENSILE PROPERTIES 0F S-200F

Temp. (F)	Orient.	Ultimate Tensile Strenght (ksi)	Yield Strength 0.2% Offset (ksi)	Yield Point			Reduction in Area (%)
				Upper (ksi)	Lower (ksi)	E long. (%)	
RT	L T	55.4 ±0.3 59.1 ±0.7	38.2 ±0.5 38.0 ±0.1	38.9 ±0.3 39.6 ±0.5	38.1 ±0.3 38.0 ±0.1	3.4 ±0.3 6.1 ±0.5	3.3 ±0.3 5.9 ±0.2
400	L T	48.1 ±0.5 48.4 ±0.3	37.1 ±0.7 37.7 ±0.5	37.7 ±0.1 38.0 ±0.2	37.0 ±0.6 37.1 ±0.1	12.0 ±1.3 29.5 ±4.1	11.2 ±1.4 25.9 ±3.3
800	L T	35.4 ±0.4 34.2 ±0.9	29.4 ±0.8 27.2 ±0.7	29.6 ±0.7 27.6 ±0.8	28.5 ±0.5 26.5 ±0.7	30.4 ±2.4 33.4 ±0.2	52.5 ±1.2 54.0 ±0.2
1000	L T	28.9 ±0.1 28.4 ±0.1	20.8 ±0.1 20.9 ±0.7	--(2) 21.2 ±0.5	--(2) 20.9 ±0.7	22.4 ±0.8 25.7 ±0.6	29.4 ±2.2 33.9 ±1.7
1200	L T (1)	15.7 ±0.3 15.5 ±0.6	13.0 ±0.5 13.8 ±0.5	13.5 ±0.9 --(2)	12.5 ±0.4 --(2)	8.8 ±1.4 10.9 ±2.1	7.3 ±0.4 9.7 ±2.0

(1) Average of 4 specimens
(2) Did not have a yield point

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14710 W Portage River South Rd
Elmore, OH 43416-9502
phone: 419.862.4533 or 419.862.4171 Intl: 419.862.4127
e: berylliumandcomposites@materion.com

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Table 3 - ELASTIC PROPERTIES FROM PRECISION ELASTIC LIMIT TESTS AT ROOM TEMPERATURE

Orientation	P.E.L. (ksi)	Yield Strength 0.01% Offset (ksi)	Young's Modulus (msi)
L	4.7 ±0.4	27.6 ±0.6	45.1 ±1.0
T	5.0 ±0.3	29.5 ±0.7	44.9 ±0.7

Table 4 -
COEFFICIENT OF THERMAL EXPANSION FOR S-200F AND S-200E OVER 5°C TO 65°C

Direction	S-200F Lot 3001 Min/in/°C	S-200E Lot 2765 Min/in/°C
L	11.39	11.39
T1	11.57	11.76
T2	11.45	11.82

Table 5 - SHEAR PROPERTIES OF S-200F AT ROOM TEMPERATURE

Orientation	Shear Modulus (msi)	Shear Rupture Modulus (ksi)
L	19.5 ±0.7	43.1 ±1.9
T	19.4 ±0.4	44.8 ±1.2

Table 6 - NOTCHED TENSILE PROPERTIES OF S-200F

Temperature (F)	Orientation	Stress Concentration Factor K_t	Notch Tensile Strength (ksi)	Notch-Strength Ratio NSR
RT	L	3.07 ±0.04	55.9 ±2.2	1.01 ±0.04
	T	3.01 ±0.05	60.3 ±1.1	1.02 ±0.03
400	L	3.05 ±0.03	58.0 ±1.2	1.21 ±0.03
	T	3.02 ±0.12	58.5 ±1.1	1.21 ±0.03

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14710 W Portage River South Rd
Elmore, OH 43416-9502
phone: 419.862.4533 or 419.862.4171 Intl: 419.862.4127
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Table 7 - ROOM TEMPERATURE FATIGUE PROPERTIES OF S-200F

Specimen Number	Test Number	Max. Stress (ksi)	Cycles ($x 10^3$)	Results[1]
Transverse Group				
T-A-120	15	40.0	377	GSF
T-A-121	16	40.0	686	GSF
T-A-125	19	39.0	1,309	GSF
T-A-134	23	39.0	4,033	GSF
T-A-130	20	39.0	15,766	RO
T-A-113	10	38.0	210	GSF
T-A-115	11	38.0	12,262	RO
T-A-118	14	38.0	30,473	RO
T-A-108	5	36.0	13,938	RO
T-A-110	8	36.0	17,186	RO
T-A-104	1	34.0	14,649	RO
T-A-106	4	34.0	30,819	RO
Longitudinal Group				
L-E-216	17	40.0	135	GSF
L-E-222	18	40.0	141	GSF
L-E-227	22	39.0	229	GSF
L-E-224	21	39.0	233	GSF
L-E-213	12	38.0	14,860	RO
L-E-220	13	38.0	15,609	RO
L-E-207	7	36.0	18,885	RO
L-E-209	9	36.0	25,686	RO
L-E-201	2	34.0	584	GSF
L-E-205	6	34.0	11,340	RO
L-E-203	3	34.0	13,554	RO

NOTES: (1) - GSF = Gage Section Failure
RO = Run Out

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e: berylliumandcomposites@materion.com

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Figure 1 - Ultimate Tensile Strength vs. Temperature for S-200F

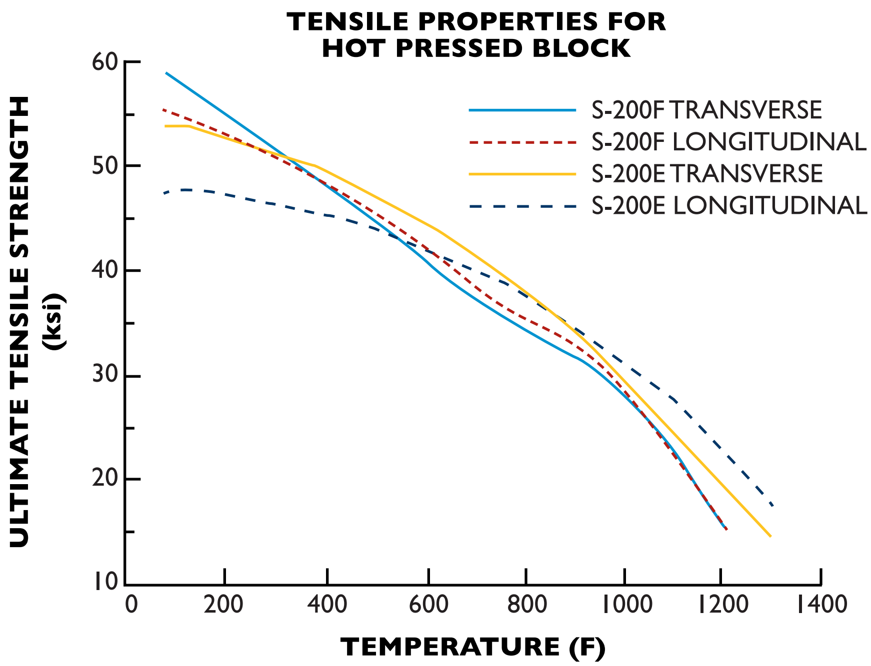
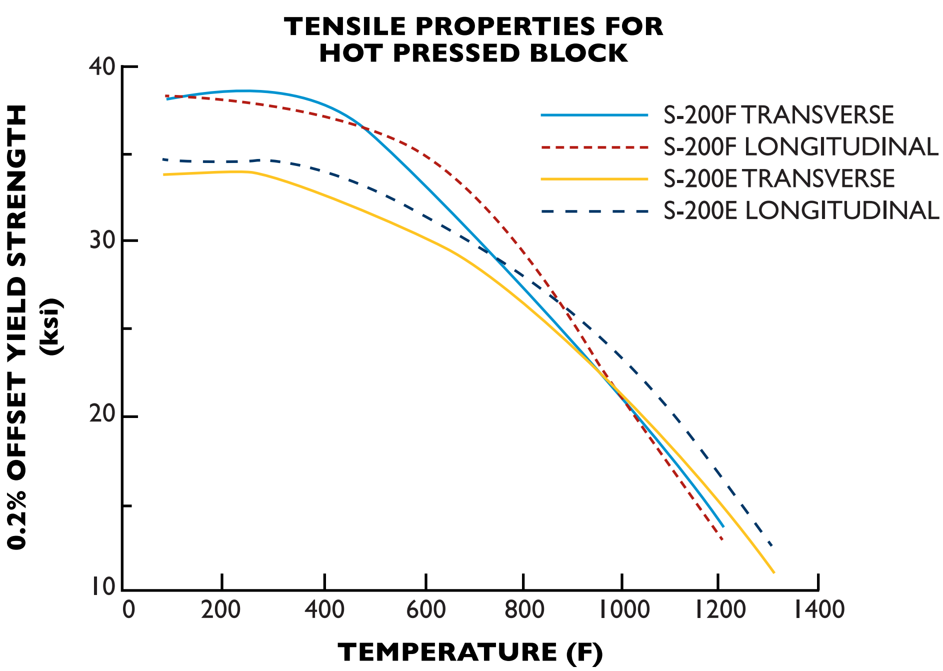


Figure 2 - Yield Strength vs. Temperature for S-200F



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Elmore, OH 43416-9502
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Figure 3 - Elongation vs. Temperature for S-200F

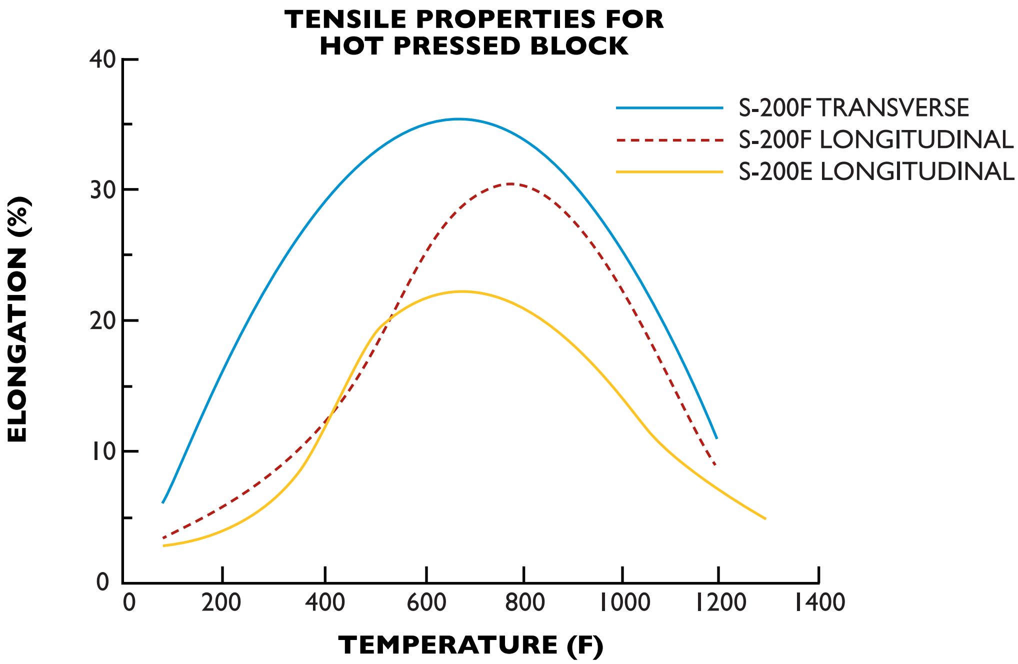

Figure 4 - S/N Curve for S-200F Tested in the Longitudinal Direction

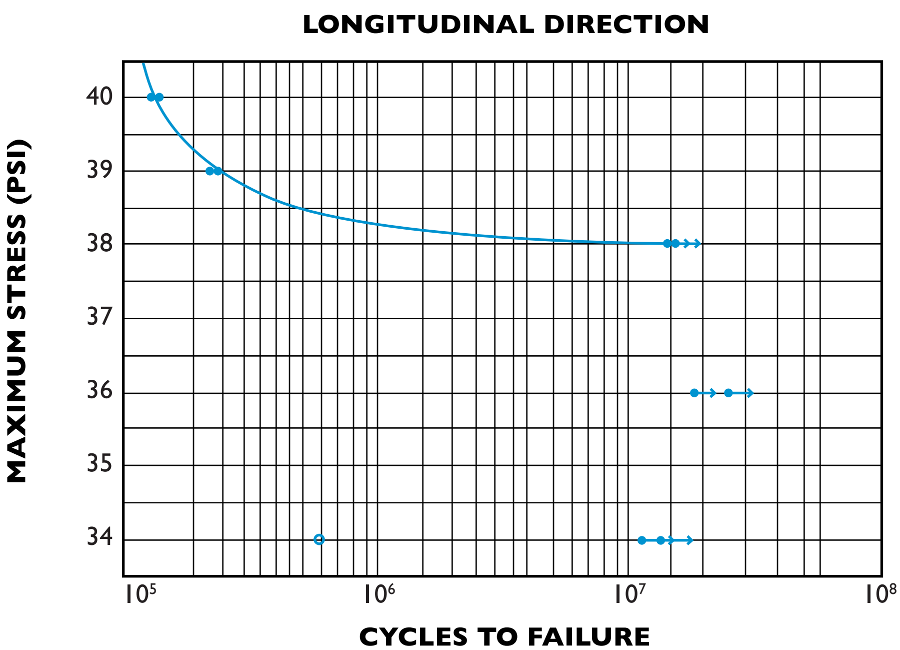

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Figure 5 - S/N Curve for S-200F Tested in the Transverse Direction

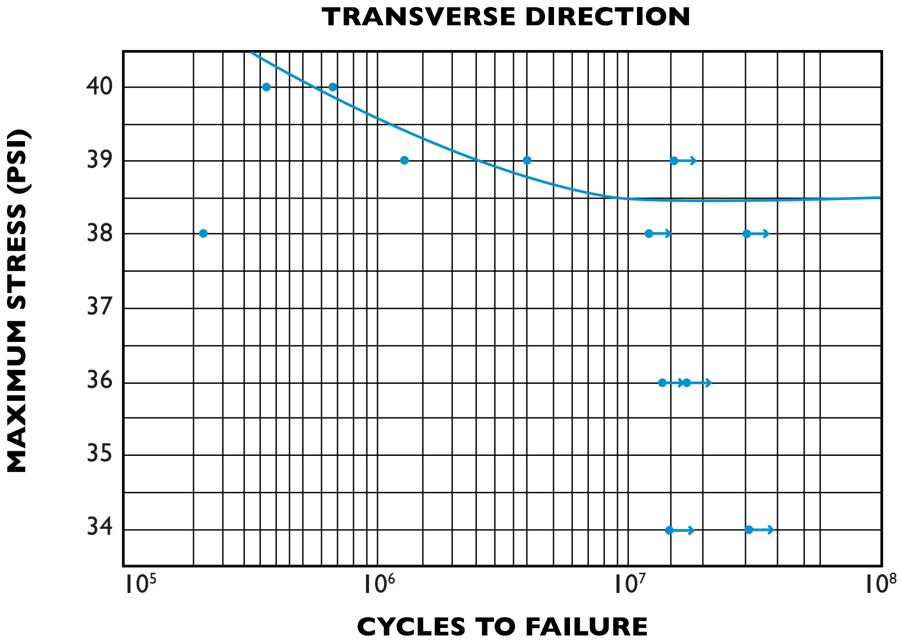
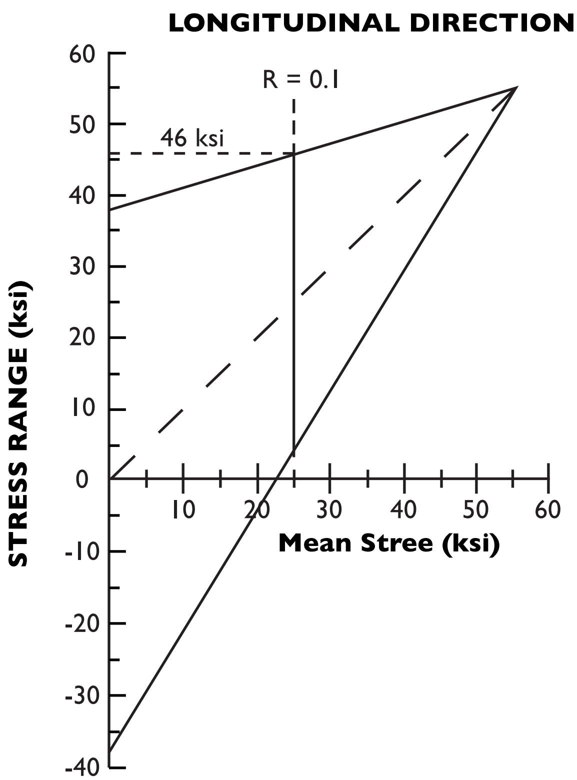


Figure 6 - Goodman Diagram for S-200F Longitudinal Direction



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e: berylliumandcomposites@materion.com

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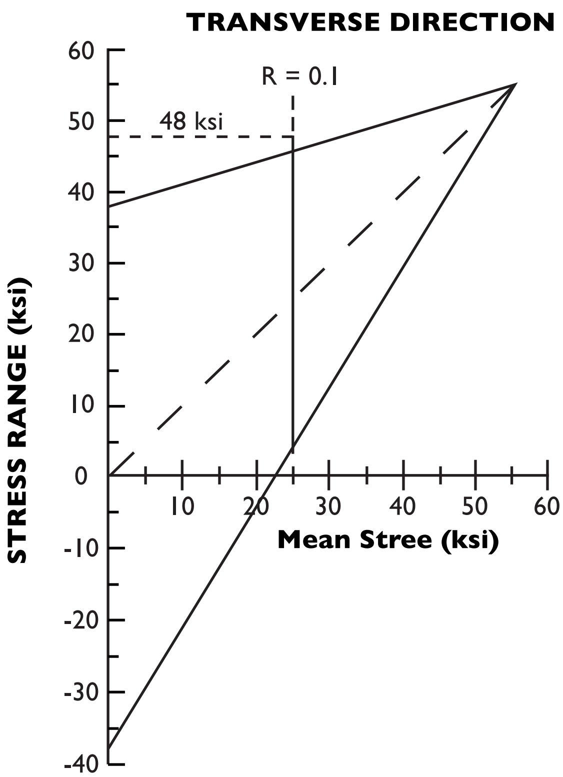
Figure 7 - Goodman Diagram for S-200F Transverse Direction



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e: berylliumandcomposites@materion.com

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Prepared by: Warren J. Haws

Warren J. Haws
Senior Metallurgist
Beryllium Research

Approved by: James M. Marder

James M. Marder
Supervisor
Beryllium Research

Approved by: A. Lames Stonehouse

A. Lames Stonehouse
Technical Director
Metal/Minerals Division

/eh
cc: J. Chomich, R. Cribb, 0. Hashiguchi, T. Parsonage (10), J. Stonehouse (3), R. Sweeney, Library, File (3)

Note:
Handling Aluminum-Beryllium Alloys in solid form poses no special health risk. Like many industrial materials, beryllium-containing materials may pose a health risk if recommended safe handling practices are not followed. Inhalation of airborne beryllium may cause a serious lung disorder in susceptible individuals. The Occupational Safety and Health Administration (OSHA) has set mandatory limits on occupational respiratory exposures. Read and follow the guidance in the Material Safety Data Sheet (MSDS) before working with this material.

For additional information on safe handling practices or technical data on Aluminum Beryllium Alloys, contact Brush Wellman Inc.

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14710 W Portage River South Rd
Elmore, OH 43416-9502
phone: 419.862.4533 or 419.862.4171 Intl: 419.862.4127
e: berylliumandcomposites@materion.com

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