Cb
5.0 Mo
5.0 V
1.0 Zr

B-66

1. GENERAL
B-66 is a columbium base refractory metal alloy which exhibits high strength at temperatures in excess of 2200F, yet retains sufficient ductility for forming and welding operations by conventional methods. Optimum high temperature properties are not dependent upon strain hardening. The alloy is available in most mill product forms and can be supplied in either the stress relieved or recrystallized conditions, depending on the requirements of subsequent fabrication and service. The oxidation resistance of B-66 is somewhat superior to unalloyed columbium. However, a protective coating is required for extended use at elevated temperatures in an oxidizing environment. Machinability and formability are good and the alloy is readily welded by TIG methods with proper procedures. B-66 is considered for high temperature applications such as leading edges for hypersonic and re-entry vehicles, rocket-engine components, reaction chambers, nozzles, gas turbine parts and fasteners, (1)(11)(12).

1.01 Commercial Designation
B-66.

1.02 Alternate Designation
Westinghouse B-66.

1.03 Specifications
None.

1.04 Composition
Table 1.04.

TABLE 1.04

Source	(1)(11)(12)		
	Percent Min	Percent Max	Percent Nominal
Carbon	-	0.020	0.006
Molybdenum	4.5	5.5	5.0
Nitrogen	-	0.020	0.006
Oxygen	-	0.030	0.012
Vanadium	4.5	5.5	5.0
Zirconium	0.85	1.3	1.0
Columbium	Balance		Balance

1.05 Heat Treatment
1.051 Stress relief. 1800F, 1 hour in vacuum.
1.052 Recrystallize. 2500F, 1 hour in vacuum, (11).
1.0521 Recrystallization properties, Table 1.0521.

TABLE 1.0521

Source	(11)			
Alloy	B-66			
Condition	Recrystallized			
	35 to 40% CW		85 to 90% CW	
Ann Temp - F	DPH hardness	% recrystall*	DPH hardness	% recrystall*
RT	300-310	0	320-325	0
1800	-	-	275-280	5
2000	252	0	230	85-95
2200	249	5	228	95
2400	235	95	-	-
2500	-	-	228	100
2600	227	-	-	-

* Metallographic

1.06 Hardness
See also Table 1.0521.
1.061 Hardness values for alloy in various conditions, Table 1.061.

TABLE 1.061

Source	(11)(12)		
Alloy	B-66		
Condition	As rolled	Stress relief 2000F, 1 hr	Recrystall 2500F, 1 hr
Hardness, DPH	325	260	230
RB	-	-	90
RC	35	20	-

1.062 Effect of elevated temperatures on hot hardness of alloy, Fig. 1.062.
1.063 Results of Knoop hardness measurements (200 g load), Fig. 1.063.

1.07 Forms and Conditions Available
1.071 The alloy is available as sheet, plate, strip, foil, bar, wire, forgings and extrusions, (11).
1.072 Forms and sizes available, Table 1.072.

TABLE 1.072

Source	(12)		
Alloy	B-66		
Form	Thickness, in	Width-in max	Length or weight, max
Plate	0.200 to 2.000	18	96 in
Sheet, cut	0.010 to 0.200	18	96 in
Strip, coiled	0.010 to 0.100	18	50 lb
Foil, coiled	0.001 to 0.010	12	40 lb
Bar, dia	0.250 to 4.000	-	96 in
Wire, dia	0.050 to 0.250	-	20 lb
Forgings and extrusions	-	-	200 lb

1.08 Melting and Casting Practice

1.09 Special Considerations
1.091 In common with most refractory metal alloys, a protective coating is required for applications requiring extended service at elevated temperatures in an oxidizing atmosphere, (12).
1.092 The mechanical properties of this alloy are sensitive to strain rate. Comparison of properties should be made only at similar strain rates, (12).

2. PHYSICAL AND CHEMICAL PROPERTIES

2.01 Thermal Properties
2.011 Melting point. 4300F, (1)(11).
2.012 Phase changes
2.0121 Time-temperature-transformation diagrams
2.013 Thermal conductivity
2.014 Thermal expansion, Fig. 2.014.
2.05 Specific heat
2.016 Thermal diffusivity

2.02 Other Physical Properties
2.021 Density. 0.305 lb per cu in; 8.43 gr per cu cm, (1)(11).
2.022 Electrical resistance
4.29 microhm-in at -320F,
8.66 microhm-in at RT,
9.80 microhm-in at 210F, (1).
2.023 Magnetic properties
2.024 Emissivity
2.025 Damping capacity

	Cb
5.0	Mo
5.0	V
1.0	Zr

B-66

2.03 Chemical Properties

2.031 Oxidation. The oxidization resistance of this alloy is somewhat superior to that of unalloyed columbium. In an oxidizing environment at elevated temperatures the alloy requires a protective surface coating. Compatibility with several coating systems including Tapco's (Ti, Cr, Si) and Boeings "Disil," have been demonstrated, (11).

2.0311 Specimens coated with "Disil" have shown no coating failure for one hour in still air up to 2900F.

2.0312 B-66 sheet (0.020 inch) coated with "Sylcor" (an Al-Sn-dip type coating) has been exposed one hour at 2500F in static air without failure.

2.0313 Weight gain in static air at 2000F is reported to be 39.0 mg per cm^2 per hour, (12).

2.032 Corrosion. In general, very little is known as yet about the resistance of this alloy to various corrosive environments. Limited studies have indicated that the alloy is not compatible with hydrogen at high temperatures, (13). Specimens were heated at 3000F, 1 hour in hydrogen and cooled to RT in hydrogen at 1500F per minute. All specimens were embrittled by this exposure. Exposure to hydrogen at RT results in continuous disintegration of the alloy under certain conditions. Clean surfaces were especially susceptible to this gross "fragmentation" phenomenon. Tensile ductility was reduced in tests in hydrogen atmospheres at temperatures up to 800F, (14).

2.04 Nuclear Properties

3. MECHANICAL PROPERTIES

3.01 Specified Mechanical Properties

3.02 Mechanical Properties at Room Temperature

3.021 Tension

3.0211 Stress-strain diagrams

3.0212 Typical room temperature tensile properties of thin sheet, Table 3.0212.

TABLE 3.0212

Source		(9)	
Alloy		B-66 (a)	
Form		12 to 15 mil foil	
Condition		CW (b)	Ann (c)
F_{tu},	-ksi	162	95
F_{ty},	-ksi	140	76
e,	-percent	2.5	32

(a) Average of longitudinal and transverse properties on 2 to 3 strip coils. Anisotropy < 10 percent of strength values in cold-worked material (transverse strength is generally higher); less in annealed material.

(b) Reduced 85 to 90 percent in thickness.

(c) Recrystallized, grain size = ASTM 8 or finer.

3.0213 Room temperature properties of annealed extruded tube blanks, Table 3.0213.

TABLE 3.0213

Source		(1)		
Alloy		B-66 (a)		
Condition		As extruded	Ann 2200F, 1 hr	Ann 2600F, 2 hr
Form		Extruded tube blanks		
F_{tu},	-ksi	109.2	98.5	93.8
		109.6	100.8	94.6
F_{ty},	-ksi	84.5	77.3	74.3
		86.3	78.9	75.7
e, (4D)	-percent	23	30	30
		28	30	34
RA,	-percent	45	71	72
		51	79	70

(a) Test Rate:
0.005 in/in/min to yield, then 0.05 in/in/min to failure.

3.0214 Average room temperature tensile properties for foil, Table 3.0214.

TABLE 3.0214

Source		(1)			
Alloy		B-66 foil			
Thickness - mils		2	6		10
Direction		L	L	T	L
F_{tu},	-ksi	126.1	105	104.9	104.6
F_{ty},	-ksi	107.3	84.7	84.3	82.4
e(2in)	-percent	15.1	21.5	23.5	24.5
E,	1000ksi	14.2	15.9	15.3	15.4

Average of 5 tests
Test Rate:
0.004 in/in/min to 0.6% offset, then 0.04 in/in/min to failure.

3.0215 Effect of heat treatment on room temperature tensile properties, Table 3.0215.

TABLE 3.0215

Source		(1)(12)					
Alloy		B-66					
Condition		Stress relief (a) 1800 to 2000F, 1 hr	Recrystall (a) 2500F, 1 hr	(b)	(c)	Extruded, forged Stress relief 2000F, 1 hr	Recrystall 3270F, 1 hr
Form		Not given	Not given	Not given	0.040 in sheet	-	-
F_{tu},	-ksi	115.5	101.5	107.0	99	111.4	113.4
F_{ty},	-ksi	95	76.5	85.6	74	87.6	77.25
e,	-percent	20	26	23	24	31.4	16.6
RA,	-percent	-	-	-	-	65.6	14.3

Test Rate:
(a) 0.05 in/in/min
(b) 0.005 in/in/min through 0.6% yield, then 0.05 in/in/min to fracture
(c) 0.05 in/in/min crosshead speed

Cb
5.0 Mo
5.0 V
1.0 Zr

B-66

3.022 Compression
3.0221 Stress-strain diagrams
3.023 Impact
3.024 Bending, (See Table 3.0341).
3.025 Torsion and shear
3.026 Bearing
3.027 Stress concentration
3.0271 Notch properties
3.0272 Fracture toughness
3.028 Combined properties

3.03 Mechanical Properties at Various Temperatures
3.031 Tension
3.0311 Stress-strain diagrams
3.0312 Effect of low and elevated temperature on tensile properties, Fig. 3.0312.
3.0313 Effect of test temperature on tensile properties of recrystallized alloy, Fig. 3.0313.
3.0314 Effect of strain rate on tensile properties of recrystallized alloy, Fig. 3.0314.
3.0315 Effect of low and elevated temperature on tensile strength of stress relieved and recrystallized alloy, Fig. 3.0315.
3.0316 Effect of test temperature on tensile properties of annealed alloy, Fig. 3.0316.
3.0317 Tensile properties for sheet
3.03171 Effect of elevated temperature on tensile properties of annealed sheet, Fig. 3.03171.
3.03172 Effect of high temperature on tensile properties of sheet, Fig. 3.03172.
3.03173 Effect of test temperature on tensile properties of sheet, Fig. 3.03173.
3.032 Compression
3.0321 Stress-strain diagrams
3.033 Impact
3.034 Bending
3.0341 Minimum bend radius at room temperature and -320F, Table 3.0341.

TABLE 3.0341

Source	(1)
Alloy	B-66
Condition	Stress relief 2000F, 1 hr
Temp - F	Minimum bend radius, t
RT	1
-320	1

3.0342 Bend properties at room and low temperature for sheet, Table 3.0342.

TABLE 3.0342

Source		(10)	
Alloy		B-66	
Form		0.040 in sheet	
Condition		Ann 2000F, 1 hr	
Heat No.		DX 555	
Temp - F		Punch radius	Bend angle (unloaded)
RT	T	1t	100 (a)
RT	T	1t	102 (a)
RT	L	1t	102 (a)
RT	L	4t	107 (a)
-40	L	4t	94 (a)
-105	L	4t	97 (a)
-240	L	4t	93 (a)
-320	L	4t	91 (a)

(a) No visible crack

3.0343 Effect of low temperature on bend ductility of as-received sheet, Fig. 3.0343.
3.035 Torsion and shear
3.036 Bearing

3.037 Stress concentration
3.0371 Notch properties
3.0372 Fracture toughness
3.038 Combined properties

3.04 Creep and Creep Rupture Properties
3.041 Creep rupture curves at 2200F and 2600F, Fig. 3.041.
3.042 Creep and creep rupture curves at 1800F, 2000F and 2200F, Fig. 3.042.
3.043 Secondary creep rate at 1800, 2000 and 2200F, Fig. 3.043.
3.044 Creep rupture properties at 2000F to 3000F for sheet, Fig. 3.044.
3.045 Creep rupture properties at 2000F and 2400F for sheet, Fig. 3.045.

3.05 Fatigue Properties

3.06 Elastic Properties. See also Table 3.0214.
3.061 Poisson's ratio
3.062 Modulus of elasticity. RT (dynamic) 15.31×10^3 ksi, (12).
3.0621 Modulus of elasticity at elevated temperatures, Fig. 3.0621.
3.063 Modulus of rigidity

4. FABRICATION

4.01 Formability
4.011 The alloy can be formed, punched, blanked or sheared at room temperature without edge cracking.
4.012 Bending, brake forming, drawing and spinning operations can be performed with greater ease at slightly elevated temperatures, (12).
4.013 Arc-cast ingots can be extruded to sheet bar at 2500 to 3000F, subsequent rolling to plate can be accomplished at 2010 to 2190F, (1).
4.014 Drawing
4.0141 Warm extruded 8 inch ingot to 4 inch billet. Machine hollow, and extrude at 3000 to 3400F to tube blanks. Warm (500F) straighten and condition tube, reduce to finish size.
B-66 could not be successfully reduced from tube blanks to finish tube at room temperature, and warm temperature tube drawing (perhaps at 500F) would be required.

4.02 Machining and Grinding
4.021 B-66 is machinable with ordinary tool steels and with the use of carbon tetrachloride or similar lubricants as cutting compounds. This reduces the tendency of the alloy to tear or gall, (12).
High speed steel or carbide tools are recommended for machining operations using a large relief and top rake angle.
The following tolerances and cutting speeds are recommended for single point turning tools:

Back rake	10°
Side rake	5°
Side clearance	5°
Trail angle	45°
Nose radius	0.020 in
Cutting speeds	50 to 60 sfpm
Roughing feeds	0.008 to 0.012 ipr
Finishing feeds	0.005 to 0.006 ipr
Depth of cut	0.015 to 0.060 in

Best finishes can be achieved with sharp tools, fine feeds and finishing the work with reasonably heavy cuts.
4.022 Shaping and milling.
It is recommended to use sharp tools and sufficient rake and clearance angles for these operations, similar to those used for soft metals such as copper and aluminum.
4.023 Broaching.
This operation is not recommended because the tool tends to tear the material.
4.024 Grinding.
Rapid loading of the wheel makes this operation difficult for annealed alloy. However, work-hardened material can be ground with a carbide wheel if it is flooded with soluble oil and dressed frequently, (12).

	Cb
5.0	Mo
5.0	V
1.0	Zr

B-66

4.03 Welding

4.031 The weldability of this alloy in general is good.

4.032 Fusion welding.

Fusion welding by TIG can be satisfactorily performed under the following conditions:

Vacuum-purged weld box,
Pressure of 0.05 microns,
Backfilled with helium,
Straight polarity d.c. current.

In a helium welding atmosphere a better weld can generally be achieved than in an argon atmosphere in regard to as-welded ductility. The following typical settings are recommended:

110 amperes
0.090 arc gap
15 ipm welding speed

for a 0.065 inch butt weld in helium, (11)(12).

4.033 Effect of room and elevated temperatures on transverse buttweld tensile properties of 6-mil foil, Table 4.033.

TABLE 4.033

Source	(8)					
Alloy	B-66					
Form	6-mil foil					
Condition	As rec		TIG welded		EB welded	
Temp - F	RT	2000	RT	2000	RT	2000
F_{tu}, -ksi	103	45.8	108	49.4	103.8	49.9
F_{ty}, -ksi	78.3	40.7	82.3	42.3	82.7	42.6
e(1in) -percent	29	45	20(a)	14(a)(b)	12.7(bc)	8(c)
Weld joint efficent						
F_{tu}, -percent	-	-	>100	>100	>100	>100
F_{ty}, -percent	-	-	>100	>100	>100	>100

(a) Parent metal failure
Heat-affected-zone failure
Weld failure

(b) Parent metal failure
Edge of weld

(c) Edge of weld

EB Electron-Beam

4.034 Bend properties at room and low temperatures for welded sheet, Table 4.034. (See also 3.0341).

TABLE 4.034

Source	(10)	
Alloy	B-66	
Form	0.040 in sheet	
Condition	As welded (TIG)	
Temp - F	Punch radius	Bend angle unloaded
RT	4t	106 (a)
RT	2t	94 (a)
RT	1t	102 (b)
-40	4t	102 (c)
-105	4t	104 (c)
-240	4t	59 (d)
-320	4t	5 (d)

(a) No visible cracks
(b) Slight surface cracking
(c) Cracked thru weld
(d) Complete fracture

4.035 Hardness values of electron beam and TIG welded sheet, Fig. 4.035.

4.036 Bend ductility of TIG and electron beam welded sheet, Fig. 4.036.

4.04 Heat Treatment

4.041 If stress-relief annealing is required during severe forming operations, 2000F, 1 hour in vacuum is recommended.

4.05 Surface Treatment

4.051 Best pickling results can be achieved by using bath at temperatures from ambient to 140F.

Percentage	Reagent
20-30	HF
0-10	H_2SO_4
20-30	HNO_3
20-50	H_2O

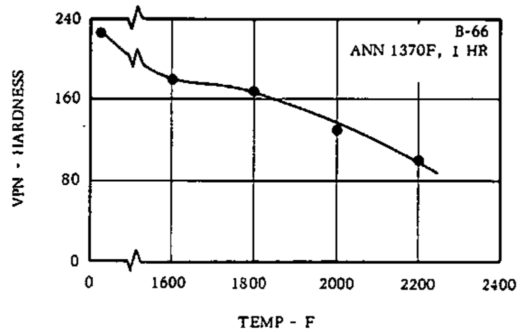

FIG. 1.062 EFFECT OF ELEVATED TEMPERATURE ON HOT HARDNESS OF ALLOY (5,p.86)

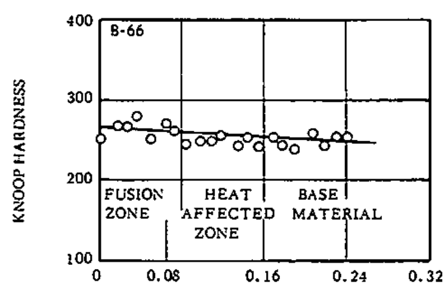

FIG. 1.063 RESULTS OF KNOOP HARDNESS MEASUREMENTS (200 g LOAD) (4,p.13)

See also Section 4.03.

Cb
5.0 Mo
5.0 V
1.0 Zr

B-66

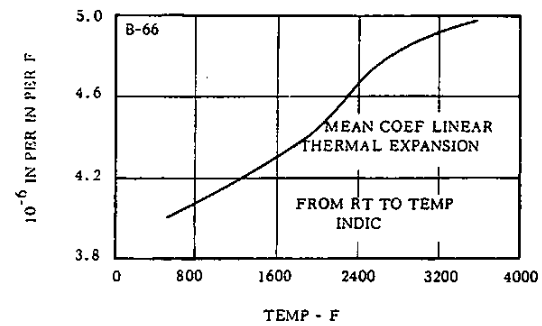

FIG. 2.014 THERMAL EXPANSION (1, A-229)(12)

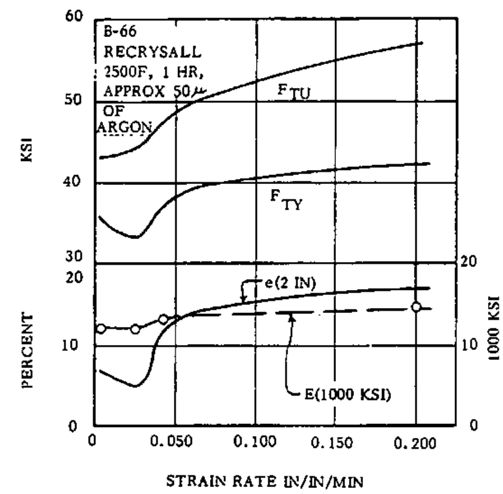

FIG. 3.0314 EFFECT OF STRAIN RATE ON TENSILE PROPERTIES OF RECRYSTALLIZED ALLOY (1, p. A-236)

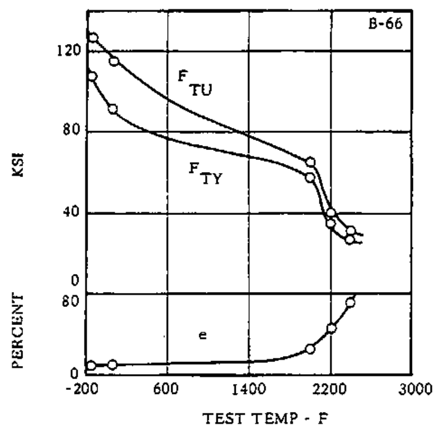

FIG. 3.0312 EFFECT OF LOW AND ELEVATED TEMPERATURE ON TENSILE PROPERTIES (6, p. 113)

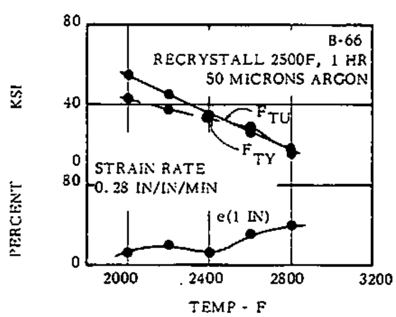

FIG. 3.0313 EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF RECRYSTALLIZED ALLOY (1, p. A-234)

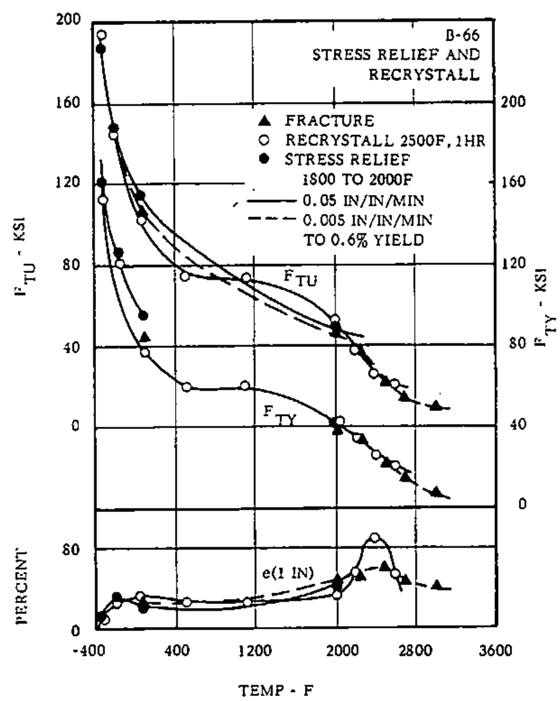

FIG. 3.0315 EFFECT OF LOW AND ELEVATED TEMPERATURE ON TENSILE STRENGTH OF STRESS RELIEVED AND RECRYSTALLIZED ALLOY (1, p. A-235)(11)(12)

Cb
5.0 Mo
5.0 V
1.0 Zr

B-66

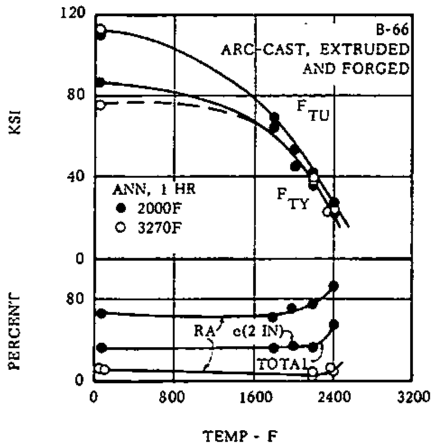

FIG. 3.0316 EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF ANNEALED ALLOY (1, p. A-233)

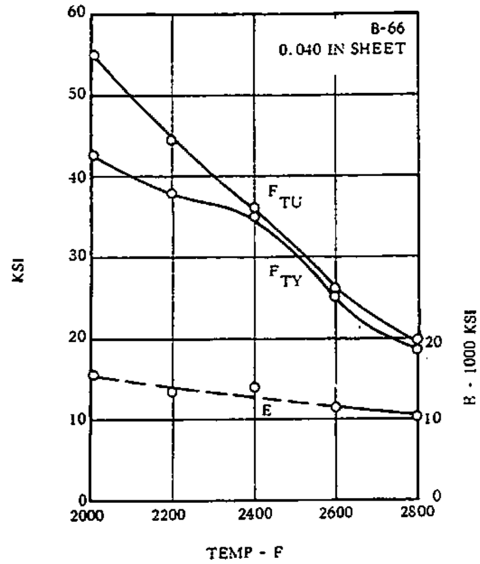

FIG. 3.03172 EFFECT OF HIGH TEMPERATURE ON TENSILE PROPERTIES OF SHEET (7, Fig. I)

Nominal Strain Rate:
0.05 in/in/min

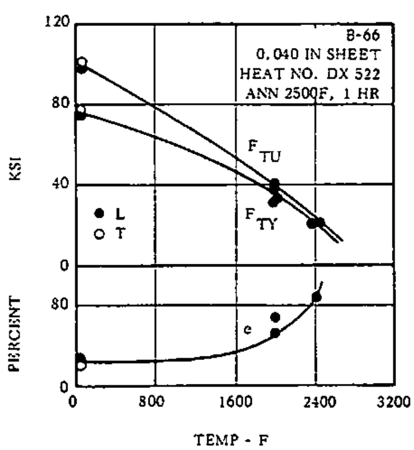

FIG. 3.03171 EFFECT OF ELEVATED TEMPERATURE ON TENSILE PROPERTIES OF ANNEALED SHEET (10, Tbl. VIII)

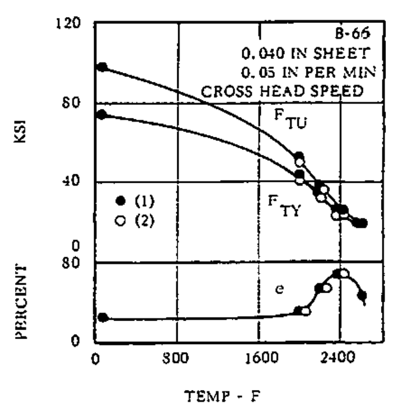

FIG. 3.03173 EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF SHEET (1, p. A-234)

Cb
5.0 Mo
5.0 V
1.0 Zr

B-66

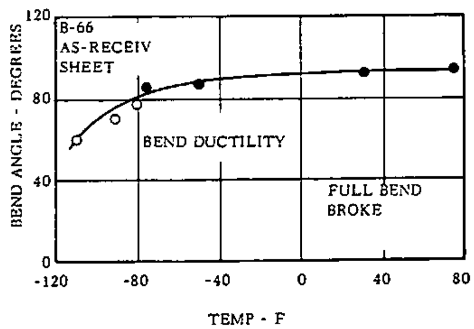

FIG. 3.0343 EFFECT OF LOW TEMPERATURE ON BEND DUCTILITY OF AS RECEIVED SHEET (15, p. 78)

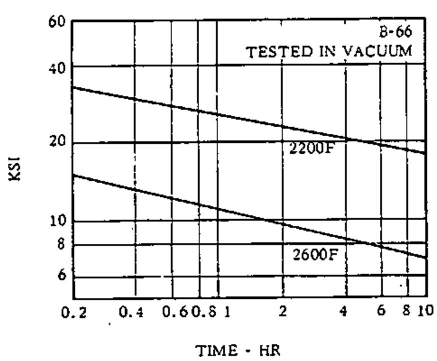

FIG. 3.041 CREEP RUPTURE CURVES AT 2200F AND 2600F (1, p. A-238)(11)(12)

Nominal analysis
Cb-5V-5Mo-1Zr-0.012O-0.006N-0.006C

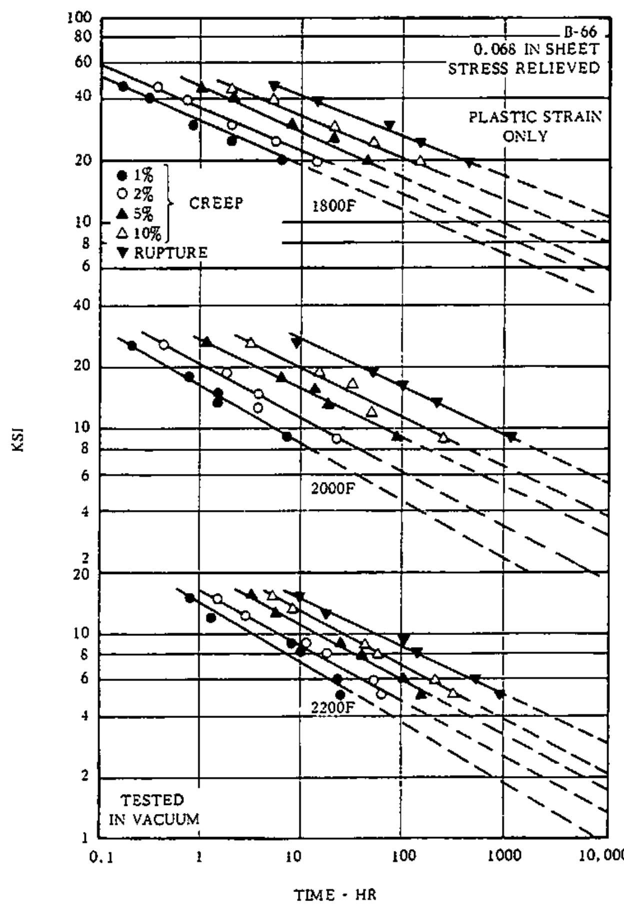

FIG. 3.042 CREEP AND CREEP RUPTURE CURVES AT 1800F, 2000F AND 2200F (3, p. 6)

	Cb
5.0	Mo
5.0	V
1.0	Zr

B-66

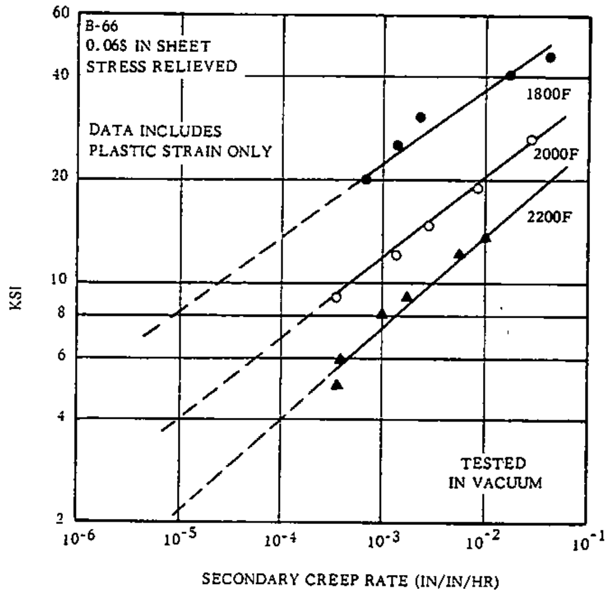

FIG. 3.043 SECONDARY CREEP RATE AT 1800, 2000 AND 2200F
(3, p. 6)

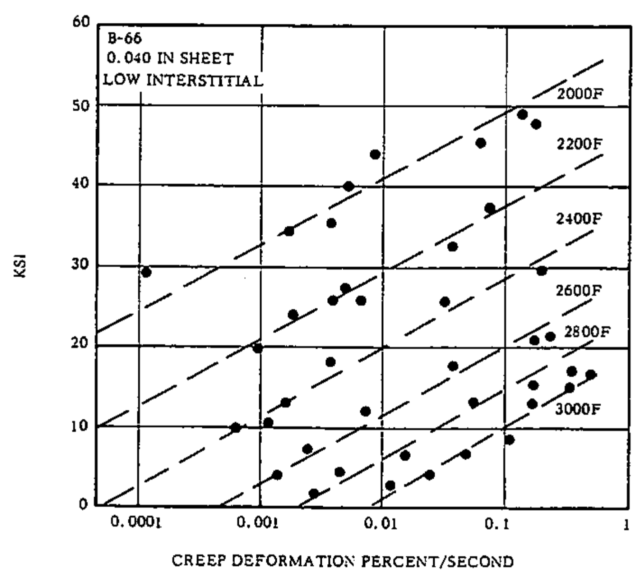

FIG. 3.044 CREEP RUPTURE PROPERTIES AT 2000F TO 3000F FOR SHEET
(7, Fig. II)

Cb
5.0 Mo
5.0 V
1.0 Zr

B-66

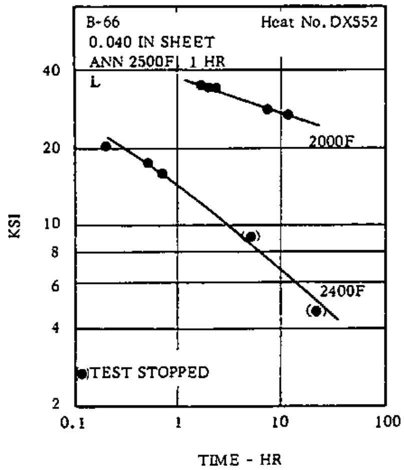

FIG. 3.045 CREEP RUPTURE PROPERTIES AT 2000F AND 2400F FOR SHEET (10, Tbl. IX)

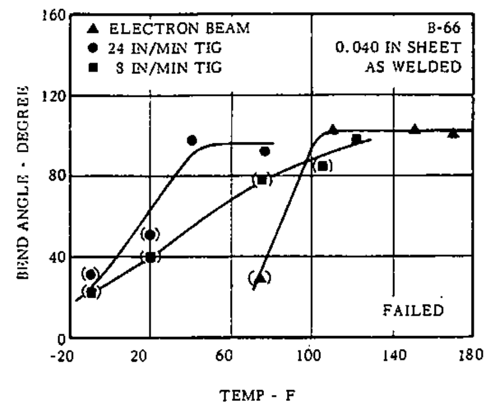

FIG. 4.036 BEND DUCTILITY OF TIG AND ELECTRON BEAM WELDED SHEET (15)

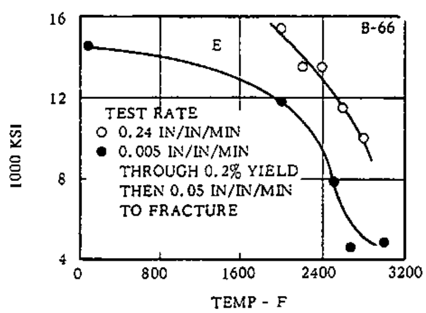

FIG. 3.0621 MODULUS OF ELASTICITY AT ELEVATED TEMPERATURES (1, p. A-236)

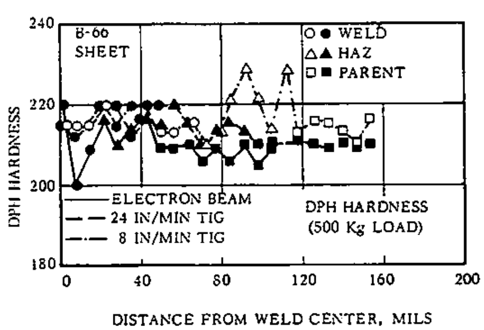

FIG. 4.035 HARDNESS VALUES OF ELECTRON BEAM AND TIG WELDED SHEET (15, p. 76)

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