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1. GENERAL

Cb-752 is a columbium-base alloy that combines high strength at elevated temperature with excellent ductility at room temperature. This alloy contains tungsten and zirconium in amounts which increase its strength by solid solution hardening with impairment of room temperature ductility. Cold rolling increases its strength but decreases its ductility. However, stress relief treatments at temperatures as low as 2000F will restore ductility with some sacrifice in strength.

Cb-752 appears to be relatively insensitive to notch stress concentration at room temperature and is thermally stable after aging for 10 hours at 2400F. Machinability is good and the alloy is readily welded by GTA methods with proper precautions. It can be fabricated by most conventional forming techniques. Resistance to high temperature oxidation is poor and protective coatings are required for high temperature applications. Current silicide coating technology can provide 150-200 hr protection at a 2500F maximum at ambient pressure and 10 hours at .01 to 50 mm Hg.

Cb-752 is considered for applications in space vehicles, nuclear reactors, jet engine structures, re-entry vehicles, thermal radiations and ducting for space power systems (1)(2)(3)(36).

1.01 Commercial Designation
Cb-752.

1.02 Alternate Designations
Haynes Alloy Cb-752.

1.03 Specifications
None.

1.04 Composition
Table 1.04.

TABLE 1.04

Source	(2)
Element	Percent Nominal
Carbon	40 ppm
Hydrogen	6 ppm
Nitrogen	<100 ppm
Oxygen	60 ppm
Tungsten	10
Zirconium	2.5
Columbium	Balance

1.05 Heat Treatment

1.051 Stress relief. 2000F, 1 hr AC produces stress relief without full recrystallization (see Figures 1.054 and 3.02171 and Table 1.055).

1.052 Recrystallize. 2200 to 2400F. This range produces maximum formability and the lowest ductile-brittle transition temperature in a bend test. Higher temperatures can produce excessive grain growth (see Figure 1.054).

1.053 Duplex anneal. 2800F, 1 hr + 40 percent CR at room temperature to final gage + 2400F, 1 hr. This is the preferred heat treatment for sheet since it gives superior tensile strength above 1800F with no sacrifice in elongation (see Figure 3.0316). Cooling rate from 2800F must exceed 2000F per hour to retain carbon and oxygen in solution so that aging at 2400F will occur (see Table 1.056).

1.054 Recrystallization characteristics, Figure 1.054.

1.055 Recrystallization behavior of sheet cold worked 50 to 97 percent, Table 1.055.

TABLE 1.055

Source	(6)(5)		
Alloy	Cb-10W-2.5Zr		
Form	Sheet		
		1 hour temperature - F	
Thickness inches	Percent Reduction	for 50 percent recrystallization	for 100 percent recrystallization
0.030	50	~2175	~2325
	75	2050	2300
	88	~2025	~2325
0.018	60	2100	2300
	70	2050	2300
	93	2050	2300
0.012	96	~2025	2300
0.008	50	2150	2300
	87	2050	2150
	97	~2025	2150

1.056 Effect of cooling rate from duplex anneal solution temperature on the room temperature tensile properties, Table 1.056.

TABLE 1.056

Source	(4)(5)					
Alloy	Cb-10W-2.5Zr					
Form	Sheet					
Thickness - inches	0.018					
Condition	Duplex Anneal (a)					
Test Temperature- F	75			2200		
Cooling Rate(b) from 2800 to 2000F, F/hr	200	500	24000	200	500	24000
F_{tu} - ksi	79	80.5	84	28.5	31.5	34
F_{ty} - ksi	57.5	60	64	22	27.5	30
e(1 in) - percent	22	21	12	39	30	18

(a) 2800F + 40 percent CR at room temperature plus 2400F for 1 hr.
(b) FC from 2000F to room temperature.

1.06 Hardness

1.061 A minimum in hardness is achieved on annealing as cold rolled sheet at approximately 2500F with secondary hardening occurring at temperatures above 2800F due to a precipitation reaction (8)(see Figure 1.054).

1.062 The duplex annealing heat treatment described in 1.053 involves four separate and distinct hardening and strengthening mechanisms described in 2.012 (37).

1.07 Forms and Conditions Available

1.071 This alloy is available in rod, bar, wire, plate, sheet, strip, forgings, forgings billets, extrusions, extrusion billets, foil, and tubing (2)(9).

1.08 Melting and Casting Practice

1.081 Established melting practice includes multiple electron beam melting to a 6 inch diameter ingot then consumable arc melting to 11 inch diameter ingot (5). This is followed by canning the ingot in Mo or steel and extrusion to billet.

1.09 Special Considerations

1.091 Heating of Cb-752 to incandescent temperatures for short times results in a contaminated surface. All testing and heat treating should be in a vacuum better than 10^{-5} torr. When ultra pure He or A is used, material should be wrapped in Ta foil.

1.092 Creep testing for periods over 100 hours at 1800F or above must be conducted in a vacuum of 10^{-8} torr. or less.

	Cb
10	W
2.5	Zr

Cb-752

2. PHYSICAL AND CHEMICAL PROPERTIES

2.01 Thermal Properties

2.011 Melting range. Melting point is 4400F (10).

2.012 Phase changes. The duplex annealing treatment brings into play four separate and distinct strengthening mechanisms. The first of these is the solid solution strengthening effect provided by tungsten and zirconium. Second is a dispersion strengthening effect with the relatively insoluble monoclinic form of ZrO_2. Third, precipitation strengthening results from the precipitates (Cb, Zr)C and face centered cubic ZrO_2 formed on aging. Fourth, the intermediate cold reduction introduces some strain hardening of the material which is not entirely relieved during the 2400F aging treatment incorporated in the duplex annealing treatment. It is obvious, then, that the duplex annealing treatment brings into play a complex set of mechanisms which strengthen the sheet. Table 2.012 presents X-ray diffraction data (5, 37).

TABLE 2.012

Source	(37)					
Alloy	Cb-10W-2.5Zr					
Form	0.030 inch sheet					
Condition	Phases Present					
	(Cb, Zr)C (a) (fcc)		ZrO_2 (monoclinic)		ZrO_2 (fcc)	
	d(Å)	Intensity	d(Å)	Intensity	d(Å)	Intensity
A Soln annealed, 2800F + CR 40 percent	2.63	weak to medium	3.15	strong	-	none
B A + 1900F, 2 hr age	2.65	medium	3.16	weak	-	none
C A + 2200F, 2 hr age	2.63/2.68(b)	strong	3.16	weak	2.95	weak
D A + 2400F, 2 hr age	2.65	strong	3.13	weak to medium	2.92	medium
E A + resoln 2800F + slow cool at 200F/hr	2.65	strong	3.15	medium	2.93	medium

(a) Pattern was obtained that gave lattice constant corresponding to a complex (Cb, Zr) carbide containing about 65 percent A/O Zr.
(b) Line for carbide phase was split giving the two values noted.

2.013 Thermal conductivity, Figure 2.013.
2.014 Thermal expansion, Figure 2.014.
2.015 Specific heat, Figure 2.015.
2.016 Thermal diffusivity.

2.02 Other Physical Properties

2.021 Density. 0.326 lb per cu in; 9.01 gr per cu cm (2).
2.022 Electrical resistivity.
2.023 Magnetic properties.
2.024 Emittance.
2.0241 Emittance (normal) of coated and uncoated sheet, Figure 2.0241.
2.0242 Emittance values between 0.7 and 0.8 were obtained for coated specimens tested in flowing air at pressures from 30 to 90 torr, and at temperatures between 1600 to 3200F. Specimens were coated with slurry aluminide (LB-2) and slurry silicides (R-512A and TS-137). Rapid heating (1000F/min) produced higher emittances than specimens heated at a rate of 400F per hour (11).
2.025 Damping capacity.

2.03 Chemical Properties

2.031 The resistance to oxidation at high temperatures is poor and the alloy must be coated when used for high temperature applications.

2.032 Short time high temperature exposure during the manufacture of bar stock does not cause serious oxidation problems.

2.033 Specimens exposed to refluxing potassium for 4000 hrs at 2200F showed no corrosion (12). When specimens are doped with oxygen at 1830F, they are severely attacked by lithium at 1830F in 100 hours. Heat treatment at 2370 to 2900F prior to lithium exposure eliminates the corrosive attack.

2.04 Nuclear Properties

3. MECHANICAL PROPERTIES

3.01 Specified Mechanical Properties

3.011 Producers specifications, Table 3.011.

TABLE 3.011

Source	(4)	
Alloy	Cb-10W-2.5Zr	
Condition	Duplex Anneal	
Thickness	Various	
Temperature - F	RT	2200
F_{tu} - ksi	75	30
F_{ty} - ksi	60	25
e (2 in) - percent	15	15

3.02 Mechanical Properties at Room Temperature

3.021 Tension.
3.0211 Stress-strain diagrams.
3.0212 Tensile properties. 0.012 to 0.030 inch thick coated and bare sheet, Table 3.0212.

TABLE 3.0212

Source	(8)							
Alloy	Cb-9.9W-2.6Zr-0.003C							
Condition	Cold worked and annealed 2300F, 1 hr (30 inch width)							
Coating	TRW Cr-Ti-Si							
Thickness - inch	0.012		0.018				0.030	
Direction	T		T		L		T	
	bare*	coated+	bare*	coated+	bare*	coated+	bare*	coated+
F_{tu} - ksi	83.4	64.5	80.2	67.7	79.5	65.8	85.4	70.7
F_{ty} - ksi	58.0	54.2	61.3	57.7	63.5	53.3	64.2	59.1
e (2 in) - percent	20.3	10.8	23.0	14.8	21.8	15.4	20.7	16.6
E - 10^3 ksi	15.6	13.6	14.9	13.9	15.7	14.5	15.4	14.5

* Strain rate 0.005 in/in/min to yield, 0.05 in/in/min to failure.
\+ Strain rate 0.005 in/in/min to yield, 0.005 in/in/min to failure. Strength values based on cross sectional area after coating.

Cb
10 W
2.5 Zr

Cb-752

3.0213 Room temperature tensile properties of bar, Table 3.0213.

TABLE 3.0213

Source	(6)
Alloy	Cb-10.2W-2.7Zr-0.007C
Form	0.250 inch diameter bar
Condition	Not specified, probably annealed
F_{ty} - ksi	87.2
F_{tu} - ksi	68.5
e - percent	31.0
RA - percent	61
Test rate 0.005 in/in/min to yield, 0.05 in/in/min to failure.	

3.0214 Tensile properties of sheet.

3.02141 Effect of annealing temperature on room temperature properties of electron beam melted sheet, Figure 3.02141.

3.02142 Effect of annealing temperature on room temperature properties of sheet, Figure 3.02142.

3.02143 Effect of sheet thickness on room temperature tensile properties, Figure 3.02143.

3.0215 Tensile properties for swaged tubing at room temperature, Table 3.0215.

TABLE 3.0215

Source	(14)		
Alloy	Cb-10W-2.5Zr		
Form	Tubing (planetary ball swaged)		
Condition	As cold worked (38 to 46 percent)		
Test Data	Room temperature tensile		
Wall Thickness-inch	0.010	0.015	0.020
Diameter - inch	0.125	0.250	0.500
F_{tu} - ksi	113.0	110.5	110.3
F_{ty} - ksi	100.5	96.8	47.7
e(4 in) - percent	2.5	6.2	-

3.022 Compression.

3.0221 Stress-strain diagrams.

3.0222 Average value of 50.9 ksi for 0.030 inch sheet in the duplex annealed condition. Coated sheet (LB-2) will have 20-50 percent higher properties (15).

3.023 Impact.

3.024 Bending.

3.0241 Minimum bend radius for sheet of between 0.008 and 0.030 inch is less than 1T at room temperature. A ductile brittle transition temperature for this same thickness range is between -250F and -320F for a 2T radius (16)(17).

3.025 Torsion and shear.

3.0251 Shear strength for 0.012, 0.018 and 0.030 inch sheet, cold worked and annealed at 2300F, 1 hr is approximately 60-62 ksi in the longitudinal and transverse condition (8).

3.026 Bearing.

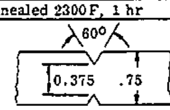
3.027 Stress concentration.

3.0271 Notch properties.

3.02711 Notch strength ratio data for a stress concentration factor (K_t) of 3.0 show no evidence of notch sensitivity down to -320F. Coating with TRW Cr-Ti-Si increases the asset of notch sensitivity to room temperature (8) (See Table 3.02712 for specimen).

3.02712 Notched tensile properties at room and cryogenic temperatures, Table 3.02712.

TABLE 3.02712

Source	(8)											
Alloy	Cb-10W-2.5Zr											
Form	Sheet											
Condition	Cold worked, annealed 2300F, 1 hr											
Notch	$K_t = 3.0$ Notch Radius = 0.0275 inch 											
Thickness - inch	0.012			0.018						0.030		
Direction	T			T			L			T		
Temperature - F	70	-110	-320	70	-110	-320	70	-110	-320	70	-110	-320
F_{tu} - ksi	83.4	103.3	148.1	80.2	99.7	142.1	79.5	97.8	139.8	85.7	105.6	147.2
NTS - ksi	94.5	116.0	148.1	90.7	115.5	149.3	88.9	108.0	153.2	94.0	119.8	166.4
NTS/F_{tu}	1.13	1.12	1.0	1.13	1.16	1.05	1.12	1.10	1.10	1.10	1.13	1.13

3.02713 Notched tensile properties of coated Cb-752 at room and cryogenic temperatures, Table 3.02713.

TABLE 3.02713

Source	(8)											
Alloy	Cb-10W-2.5Zr											
Form	Sheet											
Condition	Cold worked, annealed 1 hr, 2300F											
Coating	TRW Cr-Ti-Si											
Notch	see Table 3.02712											
Thickness - inch	0.012			0.018						0.030		
Direction	T			T			L			T		
Temperature - F	70	-110	-320	70	-110	-320	70	-110	-320	70	-110	-320
F_{tu} - ksi	64.5	74.2	76.0	67.8	76.2	41.2*	65.9	74.6	69.8	70.7	74.6	68.0
NTS - ksi	69.9	74.1	35.3	71.6	65.6	31.0	69.5	44.5	38.9	79.1	45.9	32.1
NTS/F_{tu}	1.06	0.99	0.48	1.03	0.87	<0.77	1.04	0.60	0.55	1.11	0.61	0.47
Mechanical properties based on cross sectional area after coating. * Premature failure.												

	Cb
10	W
2.5	Zr

Cb-752

3.0272 Fracture toughness.
3.028 Combined properties.

3.03 <u>Mechanical Properties at Various Temperatures</u>
3.031 Tension.
3.0311 Stress-strain diagrams.
3.03111 Stress-strain curves in tension at room temperature for several sheet thicknesses, Figure 3.03111.
3.0312 Average tensile values, standard deviation, and tentative minimums of duplex annealed Cb-752 from 4 thicknesses (0.008, 0.012, 0.018, and 0.030) of sheet, Figure 3.0312.
3.0313 Tensile properties at elevated temperature for bare and coated sheet, Table 3.0313.

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

3.04 <u>Creep and Creep Rupture Properties</u>
3.041 Creep rupture properties of duplex annealed sheet, Figure 3.041.

TABLE 3.0313

Source	(8)															
Alloy	Cb-10W-2.5Zr															
Form	0.018 inch x 30 inch sheet															
Condition	Cold worked, annealed 2300F, 1 hr															
Test Atmosphere	Vacuum (5 x 10^{-5} mm Hg)															
Coating	TRW Cr-Ti-Si															
Strain rate	0.05 in/in/min to failure except 1000F which is 0.005 in/in/min to yield then 0.05 in/in/min															
Test Temp - F	1000				2000				2500				3000			
Direction	T		L		T		L		T		L		T		L	
	bare	coated	bare	coated	bare	coated	bare	coated	bare	coated	bare	coated	bare	coated	bare	coated
F_{tu} - ksi *	55.8	34.8	54.0	36.3	39.5	25.3	38.0	26.9	17.7	12.4	16.6	12.9	7.7	8.8	7.8	8.6
F_{ty} - ksi *	34.4	31.4	38.5	27.9	32.4	21.3	29.3	21.0	16.6	12.1	16.3	12.5	7.7	-	7.8	-
e (2 in) - percent	12.1	4.6	14.3	6.0	45.7	13.2	> 80	19.7	> 70	35.1	> 50	16.4	> 45	75	> 45	75
E x 10^3 - ksi *	12.7	-	13.5	-	11.6	-	11.3	-	10.9	-	9.1	-	8.1	-	7.9	-

* Strength values based on cross sectional area after coating.

3.0314 Effect of elevated temperature on tensile properties of sheet, Figure 3.0314.
3.0315 Effect of test temperature on sheet given several different heat treatments, Figure 3.0315.
3.0316 Effect of test temperature on tensile properties of bar, Figure 3.0316.
3.0317 Effect of elevated temperatures on tensile properties of bolts, Figure 3.0317.
3.032 Compression.
3.0321 Stress-strain diagrams.
3.033 Impact.
3.034 Bending.
3.035 Torsion and shear.
3.0351 Effect of elevated temperature on shear strength of alloy Figure 3.0351.
3.0352 Effect of elevated temperatures on double shear strength of coated fasteners, Figure 3.0352.
3.0353 Effect of elevated temperature on the shear strength of coated (LB-2) and uncoated 0.018 inch sheet, Figure 3.0353.
3.036 Bearing.
3.0361 Effect of elevated temperatures on bearing strength of sheet, Figure 3.0361.
3.0362 Effect of elevated test temperature on bearing strength, Table 3.0362.

TABLE 3.0362

Source	(16)(4)							
Alloy	Cb-10W-2.5Zr							
Form	0.012, .018, 0.030 inch sheet							
Condition	Duplex Anneal							
Specimen Design	MIL-HDBK-5 Type							
Thickness - in	0.012	0.018						0.030
Temperature - F	RT	RT	600	1200	1800	2200	2700	RT
e/D	2	2	2	2	2	2	2	2
D/t	9:1	10:1	10:1	10:1	10:1	10:1	10:1	6:1
F_{bru} - ksi	174.0	181.6	135.2	120.1	108.4	79.3	44.1	180.9
F_{bry} - ksi	111.5	116.5	94.2	85.4	76.4	58.6	32.5	119.9

3.042 Minimum creep rate for 0.030 inch sheet at 2000 and 2200F, Table 3.042 (7).

TABLE 3.042

Source	(7)	
Alloy	Cb-10W-2.5Zr	
Form	0.030 inch sheet	
Condition	Warm-cold rolled approximately 80 percent following last in process anneal, annealed one hour and stretcher leveled	
Test Condition	10^{-8} torr vacuum	
Temperature - F	2000	2200
Stress, ksi	8.52	4.27
Min Creep Rate in/in/hr	1 x 10^{-5}	1.2 x 10^{-4}

3.043 Creep curves for sheet at 2000 and 2200F, Figure 3.043.
3.044 Creep strength versus temperature for bare and coated sheet for 1 percent creep, Figure 3.044.
3.045 Total creep curves at 1800F for duplex annealed sheet, Figure 3.045.
3.046 Total creep curves at 2200F for duplex annealed sheet, Figure 3.046.
3.047 Effect of annealing temperature on the creep properties of sheet at 1800F, Figure 3.047.
3.048 Effect of annealing temperature on the creep properties of sheet at 2200F and 17.5 ksi, Figure 3.048.
3.049 Total creep curves at 1800F and 2200F for duplex annealed sheet treated for 2900F, 1 hour prior to testing, Figure 3.049.

3.05 <u>Fatigue Properties</u>
3.051 S-N curves for coated and uncoated bolts at room temperature and 1000 to 1800F, Figure 3.051.
3.052 Stress range diagram for coated sheet at room temperature, Figure 3.052.
3.053 Fatigue properties for coated sheet at room temperature, Figure 3.053.
3.054 Elevated temperature tension-tension fatigue tests at 2000 and 2500F and a stress ratio of 0.1 on TRW coated sheet indicate that the TRW coating withstood 10 hours (10^6 cycles) without gross coating failure. In these tests the mean stress components were sufficiently high to produce creep (6).

Cb
10 W
2.5 Zr

Cb-752

3.06 Elastic Properties
3.061 Poisson's ratio.
3.062 Modulus of elasticity.
3.0621 Modulus of elasticity of sheet, Figure 3.0621.
3.063 Modulus of rigidity.

4. FABRICATION

4.01 Formability

4.011 General. The alloy can be formed using most of the conventional forming methods and practices. Primary ingot breakdown must be done above the recrystallization temperature. Subsequent working for final forming may be accomplished in range of room temperature to 800F.

4.012 Sheet rolled from this alloy has excellent bend ductility (see section 3.0241).

4.013 Residual stresses of up to 50 ksi resulting from forming can be removed completely by an anneal of one hour at 2200F (27).

4.014 Rubber pad forming of compound flanges was effected at room temperature on a total of 13 samples from 0.018 and 0.030 inch duplex annealed sheet. The flat patterns for these had a nominal 0.69 inch flange width, and inner and outer radii on the finished flanges were 3 and 5 inches, respectively. These were formed with production equipment using the trapped rubber process at a pressure of 11,000 psi. Specimens of 0.030 inch were also impact formed with a drop hammer. Hard lead overlays, along with butyl and silicone rubber pad overlays, were used to assist the forming (4)(16).

4.015 Techniques and schedules were also established for cold dimpling 0.008, 0.018 and 0.030 inch duplex annealed sheet for 1/8 inch and No. 10 flush tension head fasteners. Dimpling was accomplished in squeeze-type pneumatically operated production equipment adapted for use with ram coin dimpling tools. The specimens were dimpled using 0.1285 inch pilot holes for the 1/8 inch dimples and an undersize 0.1520 inch pilot hole for the No. 10 (0.1935 inch) dimples. Defects (i.e., cracks and warpage) were found only in the dimple flares of the No. 10 dimples in the 0.008 inch sheet (a very severe test)(4,15).

4.016 By stress relieving at 2100F for 1 hour after a 10.5 to 12 percent prestrain, the percent elongation increased from 24 percent to 35 percent. This technique has been used in fabricating radiation heat shield panels (39).

4.02 Machining and Grinding

4.021 General. Machining characteristics of Cb-752 are good, but like most columbium alloys there is a tendency for tearing and galling unless proper machining procedures are used. In machining, high speed steel tools with high cutting speeds are recommended. Tools should be kept sharp and should be ground with as much protective rake as the strength of the tool will allow. A good water soluble oil (1 part oil to 15 parts water) should be used for lubrication and cooling. Typical machining speeds and feeds are given in Table 4.021. These may need to be modified to accommodate different equipment or configurations (2).

TABLE 4.021

Source	(2)		
Alloy	Cb-10W-2.5Zr		
Data	Guide for machining operations		
Operation	Cutting speed (sfpm)	Feed (ipr)	Depth of cut (inch)
Turning	30 to 40	0.003	-
Boring	20 to 30	0.003	-
Facing	30 to 40	0.003	-
Drilling	180	0.003 to 0.004	-
Milling	195	0.5 in/min	-
Tapping	224	Hand	0.625

4.022 Machining of ingots from billets. Ingots, induction heated in argon to 2500F-2600F and extruded at 3:1 or 4:1 ratio, have been machined to billets successfully. Swaging can also be accomplished although it creates a corrosion problem which can be overcome by heating the bar in molten glass (1).

4.023 For threading, thread grinding is advisable using a multi-pass method and dressing of the wheel after each pass. A water soluble coolant is recommended (2).

4.03 Welding

4.031 Fusion welding, by both GTA and EB processes can be accomplished readily. Cleanliness and atmospheric control must be carefully exercised (17).

4.0311 Optimum GTA weld practice for sheet 0.035 inch and less is 30 inches per minute, 3/8 inch clamp spacing, and 87 amps in a helium filled chamber with a post weld anneal of 2200F. This will produce a weldment with a -75F BDTT (bend ductile brittle transition temperature) in the longitudinal and 0F in the transverse direction with a 1T bend radius (17)(28).

4.0312 Optimum EB weld practice using high voltage equipment (150 Kv) for sheet 0.035 inch and less is 15 inches per minute, 3/16 inch clamp spacing, and 3.3 milliamperes in a vacuum chamber at 5×10^{-5} torr. with a post weld anneal of 2400F. This produces a -200F BDTT in both longitudinal and transverse directions (28).

4.0313 Roll spot welding on sheet sizes, -0.012 to 0.012, 0.012 to 0.018, and 0.018 to 0.030 inch, using electrode wheels of Ag plated Cu, Ag rimmed Cu, and Ag infiltrated tungsten was evaluated (29). Results indicate quality welds can be produced using Ag plated Cu electrodes on-0.012 to 0.012 sheet but the electrode wheels have very short lives.

4.0314 Precipitation strengthened columbium base alloys can be "brazed" using titanium alloys. In contrast to conventional brazing the titanium alloy does not melt and the joint is established through solid state diffusion processes. This method of joining is therefore better defined as bonding rather than brazing. The bonding alloy acts as an interstitial sink for the base metal and removes N, O, and C from it. Substantial reductions in strength occur as a result of this process (see Table 4.03141 and Figure 4.03142)(23).

4.03141 Tensile properties at room and elevated temperature for stress relieved sheet in the as received condition after a bonding heat treatment and after bonding, Table 4.03141.

TABLE 4.03141

Source	(23)																	
Alloy	Cb-10W-2.5Zr																	
Form	0.020 inch sheet																	
Condition	Cold worked, stress relieved (temp not specified, est. 2300F)																	
Bond Alloy	Ti-30V (see 4.0314)																	
Test Temp - F	70									2200								
Heat Treat — Temp-F		2200						2500			2200						2500	
Heat Treat — Time-hr	As rec'd	1		20		50		.75		As rec'd	1		20		50		.75	
Bonded*	-	No	Yes	No	Yes	No	Yes	No	Yes	-	No	Yes	No	Yes	No	Yes	No	Yes
F_{tu} - ksi	103.0	-	80.0	74.4	-	-	67.3	77.8	-	28.5	26.3	23.0	26.3	24.0	25.0	25.5	29.5	26.8
F_{ty} - 0.2 percent - ksi	86.7	-	66.5	56.4	-	-	64.1	61.1	-	21.5	21.7	20.4	21.7	20.4	21.0	20.3	23.8	22.7
Prop Limit - ksi	66.7	-	56.5	49.6	-	-	52.9	52.8	-	15.0	18.7	15.0	19.3	17.1	18.1	15.2	20.5	17.2

* Two sheets bonded with Ti-30V and tested as a sandwich. As received material not treated with Ti-30V foil.

	Cb
10	W
2.5	Zr

Cb-752

4.03142 Effect of annealing time on the 70 and 2200F tensile strength of 0.020 inch sheet bonded with Ti-30V, Figure 4.03142.

4.0315 Bonding using an interleaf of B-120-VCA titanium and an electron beam as a heating source proved to be difficult to control. Optimum parameters were 70 milliamperes at 30 Kv and 42 ipm (30).

4.032 Effect of welding on mechanical properties.

4.0321 Mechanical properties of GTA and EB welded sheet and plate, Table 4.0321.

TABLE 4.0321

Source	(17)(28)									
Alloy	Cb-10W-2.5Zr									
Form	0.035 inch sheet and 0.375 inch plate									
Condition	Sheet: recrystallized one hour 2200F									
	Plate: recrystallized one hour 2500F									
GTA Weld Parameters	Sheet: 30 ipm, 3/8 in clamp spacing, 87 amperes,+ 2200F anneal									
	Plate: double U joint, 3 passes with filler + 2200F anneal									
EB Weld Parameters	Sheet: 15 imp, 3/16 in clamp spacing, 3.3 milliamp + 2400F anneal									
	Sheet								Plate	
Weld Process	GTA				Base Metal				GTA	EB
Temperature - F	RT	1800	2100	2400	RT	1800	2100	2400		
F_{tu} - ksi	65.0	51	36	24	73	47	34	22	83.0	73.0
F_{ty} - ksi	-	28	25	19.5	-	27	23	15	57.1	-
e (2 in) - percent (c)	18	13	35	65	20	24	40	73	22.8	-
BDTT - F (a)	-75 to 0				-270				RT(b)	-275 to -75

(a) Bend ductile-brittle transition temperature.
(b) Bend angle for 16t, 8t, and 3 t is 25, 50, 140° respectively.
(c) e, percent in 1 inch at elevated temperatures.

4.0322 Electron beam weld joint tensile strength of uncoated and coated sheet, Table 4.0322.

TABLE 4.0322

Source	(8)							
Alloy	Cb-10W-2.5Zr							
Form	0.018 inch sheet							
Condition	Cold rolled and stress relieved 2300F, 1 hr							
Coating	TRW Cr-Ti-Si							
Weld	Electron beam (parameters not specified)							
	Uncoated				Coated*			
Test temp - F	RT	1000	2000	3000	RT	1000	2000	3000
Ftu - ksi	78.2	56.9	32.7	12.9	49.5	34.6	21.7	9.0

* Strength values based on cross sectional area after cooling.

4.0323 Effect of annealing on GTA and EB weld bend ductility, Figure 4.0323.

4.04 Heat Treatment

4.05 Surface Treatment

4.051 Acid pickling is used for descaling. Trichloroethylene or detergent washing is used to remove surface dirt and grease.

4.052 Coating.

4.0521 General. Extensive research has gone into the development of coating systems for columbium base alloys. The reader is directed to Materials Advisory Board Report 234 for detailed references.

The silicide coatings characterized by the TRW Cr-Ti-Si and the Sylvania R512E (Si-Cr-Fe) provide oxidation protection for lifetimes up to 150-200 hours at temperatures up to 2500F and can be considered for use on reentry vehicles (space shuttle, hypersonic A/C) where reuse is required without refurbishment for one or two flights. Specific testing conditions will have to be simulated to define operational capability. It should be noted that all coatings degrade base property strength values.

Specific data comparing the effect of coating on various physical and mechanical properties are given in Figures 2.0241,3.044, 3.0353, 3.052 and Tables 3.0212, 3.02713 3.0313, and 4.0322.

4.0522 TRW Cr-Ti-Si coating.

4.05221 Comparison of coating life in dynamic and static test conditions, Table 4.05221.

TABLE 4.05221

Source	(31)(36)			
Alloy	Cb-10W-2.5Zr			
Form	0.375 inch diameter rod			
Condition	Not specified			
Coating	TRW Cr-Ti-Si			
Test Condition(c)	Dynamic (a)			Static (b)
Air Stagnation Pressure, atm	0.03			0.026
Temperature - F	2880	3000	3180	2900
Coating Life, Min	5	10	11	5
Failure Mode	Incipient Melting	Melting	Melting	Melting

(a) Dynamic tests run in high enthalpy wind tunnel at NASA-LaRC.
(b) Static tests run at Lockheed-LHSC in a furnace at the same pressure conditions as (a) above.
(c) Stagnation pressure is the total pressure measured at the surface resulting from the impingement of a moving gas stream.

4.05222 Response of Cr-Ti-Si coated rod to dynamic test environments, Figure 4.05222.

4.05223 Effect of brazing cycle heat treatments and Cr-Ti-Si coating on tensile properties of sheet, Table 4.05223.

TABLE 4.05223

Source	(4)(20)													
Alloy	Cb-10W-2.5Zr													
Form	0.018 inch sheet													
Condition	not specified													
Test Temperature - F	Room Temperature (a)							2200(b)						
Material Condition*	1	2	3	4	5	6	7	1	2	3	4	5	6	7
F_{tu} - ksi	85.3	84.6	78.3	-	77.1	-	-	36.2	37.6	33.6	31.7	32.5	31.4	26.7
F_{ty} - ksi	69.8	69.3	62.3	-	57.4	-	-	26.0	29.4	28.3	25.1	25.7	27.0	21.9
e - percent	27	23	26	-	25	-	-	31(c)	18(c)	22(c)	36(d)	32(c)	17.5(d)	26(d)

* Material Condition:
1. As received
2. Bond thermal cycle: 2200F/1 hr + 3000F/15 min
3. Bond laminate + TRW coating cycle: 2300F/8 hr + 2000F/4 hr
4. TRW coated - Ti-Cr-Si
5. Bond thermal (2) + coating thermal (3)
6. Bond thermal (2) + TRW coating (4)
7. Bonded laminate: B-120 VCA at 3000F/10 min + TRW coated (4)

a. Strain rate = 0.005 in/in/min to yield, 0.05 in/in/min to fracture
b. 0.05 in/in/min to fracture
c. tested in vacuum
d. tested in air

4.05224 A comprehensive evaluation (33) of the Pfaudler PFR-32 and TRW Cr-Ti-Si coatings was made varying temperatures from 2400 to 3300F, time up to 4 hours, and pressures from 0.01 to 50 torr at air velocity of Mach 3. At 0.01 to 0.1 torr, the silicide coatings had useful coating life up to 4 hours at temperatures of 2550 to 2650F, but exhibited early failure above 2650F. Coatings withstood acoustic vibration effects and the Mach 3 airflow unless liquid or viscous conditions existed on the surface.

4.0523 Sylvania R512E (Si-20Cr-20Fe) coating.

4.05231 Cyclic oxidation tests at 2600F (15 minute slow heat-up to 2600F, one hour at 2600F, 15 minute cool-down to room temperature) on the Sylvania R-512E slurry silicide (Si-20Cr-20Fe, fired at 2500F in a vacuum retort) were conducted (32) on 10 inch and 12 inch long panels. A Weibull plot of these data are given in Figure 4.05231.

4.05232 A screening test program was conducted (32) on the Sylvania R-512-E coating on tube shapes in various combinations of temperature, pressure, and corrosive environment. Parameters included temperatures of 2650 and 2800F, pressures were 45 and 75 psia, and environments of $80N_2/20O_2$ and $90N_2/10O_2$. The effect of the high pressure environment on the coating behavior was more severe at the 3 atmospheres level that at the 5 atmospheres because of the increased gas diffusion.

4.05233 The Sylvania R512E (20Cr-20Fe-60Si) coating protected sheet over 8 hours at 2600F at 0.1 torr, and over 8 hours at 2800F at 1 and 10 torr air pressure. The system also survived twenty 2.2 hour cycles of temperature up to 2500F and pressures of 0.01 to 1000 torr (simulated reentry conditions)(35).

4.0524 Miscellaneous coatings.

4.05241 Cyclic oxidation tests at 2400 and 2600F (one hour at temperature in still air and cool to ambient) on the Vac Hyd basic slurry silicide coating show a trend toward longer life exists with increased coating thickness, Figures 4.05241a and 4.05241b.

4.05242 The Solar V-(80Cr-20Ti)-Si coating reduced the tensile strength of 0.012 and 0.030 inch sheet 20-30 percent at RT and 2200F, the 10^6 cycle fatigue strength 50 percent at room temperature and caused embrittlement at room temperature (34).

4.05243 Response of $Cr-MoSi_2$ coated rod to dynamic test environments, Figure 4.05243.

	Cb
10	W
2.5	Zr

Cb-752

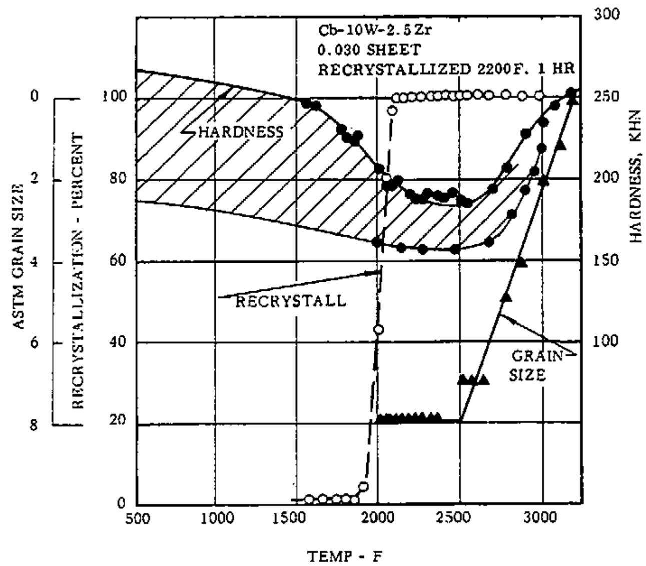


FIG. 1.054 RECRYSTALLIZATION CHARACTERISTICS. (6, p. A-161)

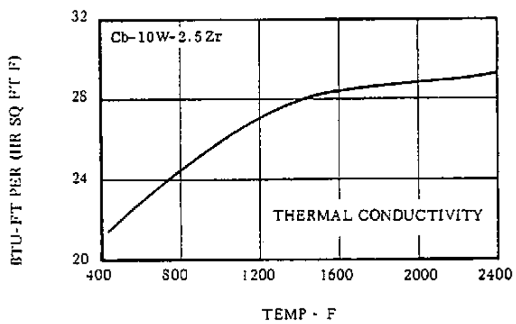


FIG. 2.013 THERMAL CONDUCTIVITY. (5)

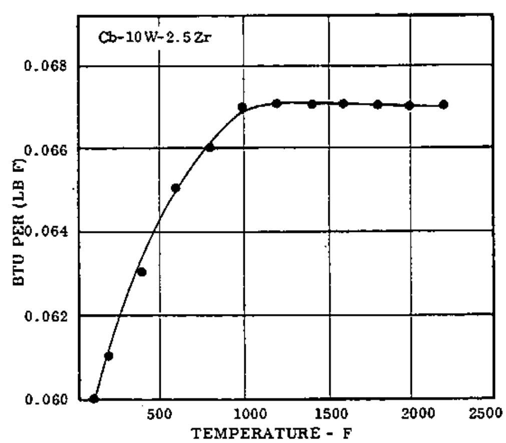


FIG. 2.015 SPECIFIC HEAT. (5)

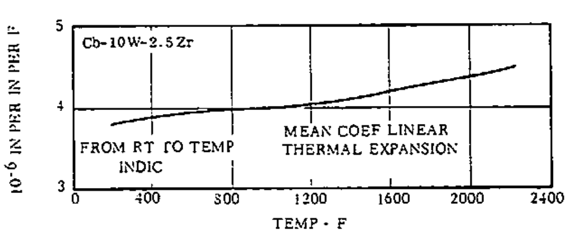


FIG. 2.014 THERMAL EXPANSION. (5)

Cb
10 W
2.5 Zr

Cb-752

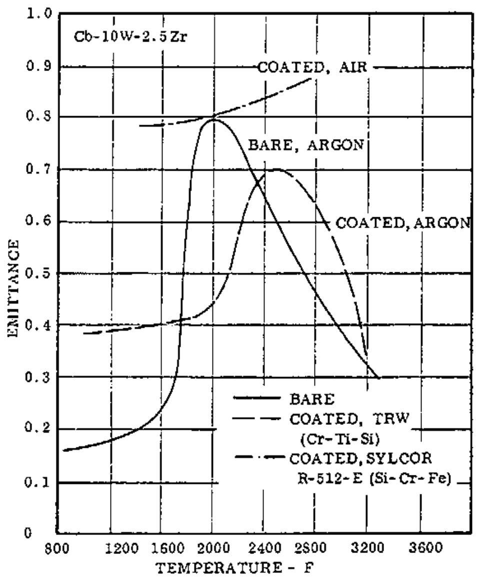


FIG. 2.0241 EMITTANCE (NORMAL) OF COATED AND UNCOATED SHEET. (8)(38)

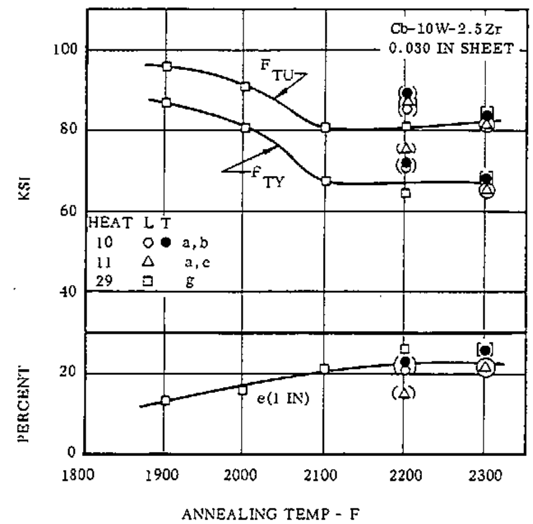


FIG. 3.02142 EFFECT OF ANNEALING TEMPERATURE ON ROOM TEMPERATURE PROPERTIES OF SHEET (5, p. A-149)

Note:
( ) Avg. from two tests
[ ] Avg. from eight tests
◯ Avg. from ten tests
(a) Test Rate: 0.005 in/in/min to yield + 0.02 in/in/min to failure
(b) 9.45W, 2.45Zr, 0.01C, 0.027O, 0.0024H, 0.004N
(c) 10.04W, 3.23Zr, 0.027C, 0.047O, 0.0043H, 0.004N
(g) Avg. from four tests
Test Rate: 0.005 in/in/min to yield + 0.05 in/in/min to failure

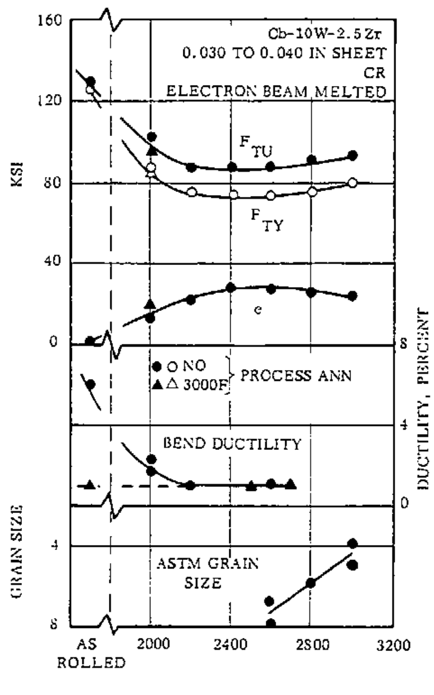


FIG. 3.02141 EFFECT OF ANNEALING TEMPERATURE ON ROOM TEMPERATURE PROPERTIES OF ELECTRON BEAM MELTED SHEET. (3, p. 164)(7)

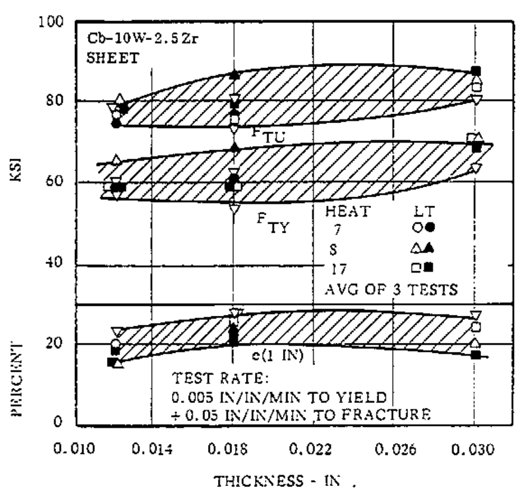


FIG. 3.02143 EFFECT OF SHEET THICKNESS ON ROOM TEMPERATURE TENSILE PROPERTIES (5, p. A-147)(7)

Heat	W	Zr	C	O	H	N
7	10.06	2.45	0.004	0.005	0.0006	<0.010
8	10.49	2.54	0.003	0.004	0.0007	<0.010
17	10.20	2.46	0.002	0.010	0.0006	<0.010

	Cb
10	W
2.5	Zr

Cb-752

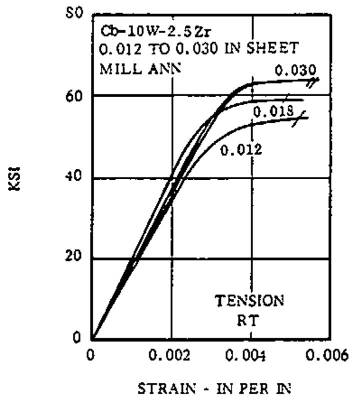


FIG. 3.03111 STRESS-STRAIN CURVES IN TENSION AT ROOM TEMPERATURE FOR SEVERAL SHEET THICKNESSES (3, p. 59)

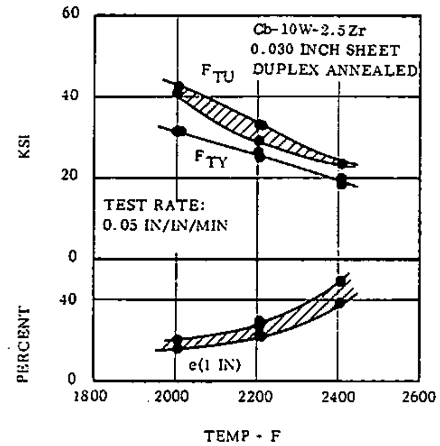


FIG. 3.0314 EFFECT OF ELEVATED TEMPERATURE ON TENSILE PROPERTIES OF DUPLEX ANNEALED SHEET. (6, p. A-152)

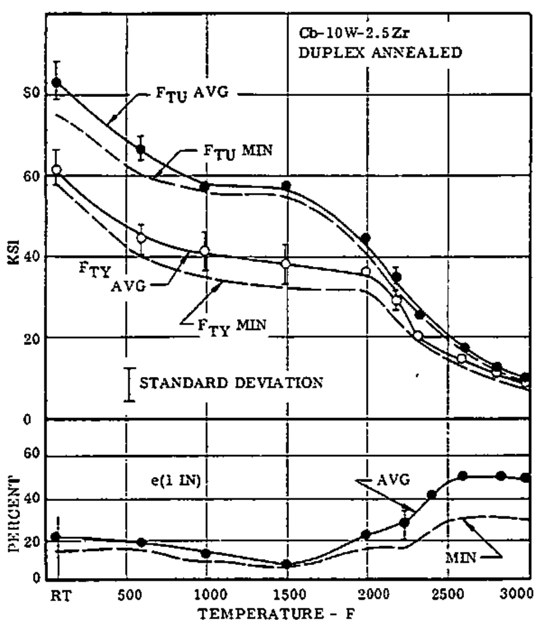


FIG. 3.0312 EFFECT OF TEST TEMPERATURE ON AVERAGE TENSILE VALUES, STANDARD DEVIATION, AND TENTATIVE MINIMUMS OF DUPLEX ANNEALED SHEET. (4)(5)(19)(20)(21)(22)

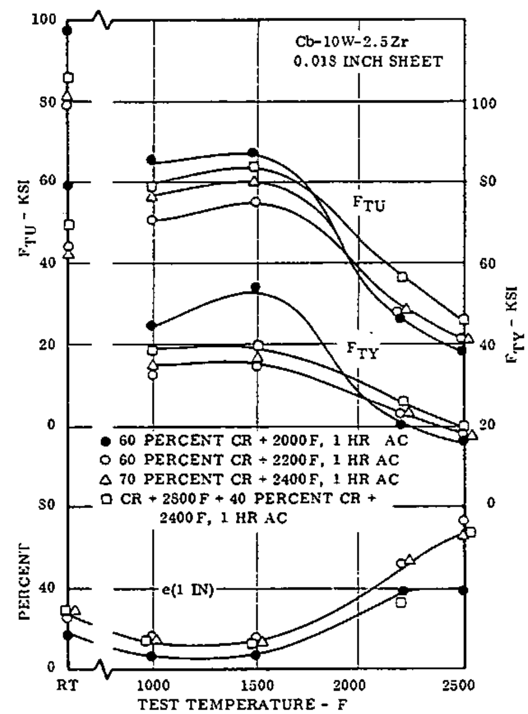


FIG. 3.0315 EFFECT OF TEST TEMPERATURE ON SHEET GIVEN SEVERAL DIFFERENT HEAT TREATMENTS. (4)(5)

	Cb
10	W
2.5	Zr

Cb-752

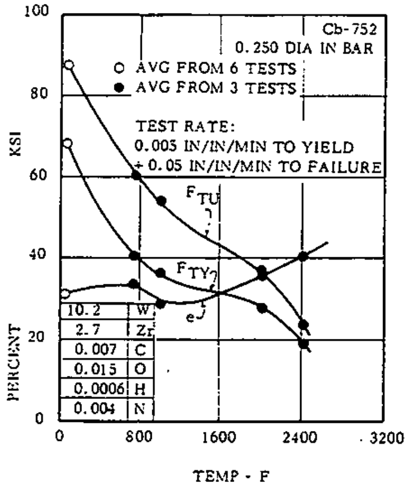


FIG. 3.0316 EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF BAR (6)

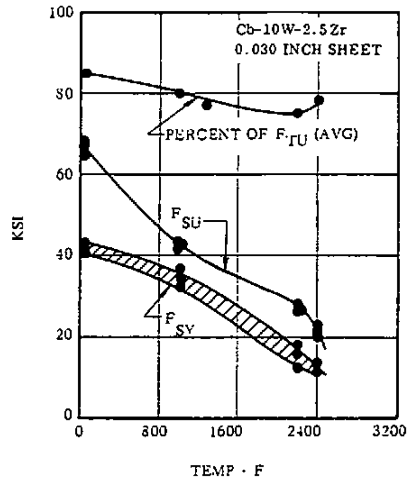


FIG. 3.0351 EFFECT OF ELEVATED TEMPERATURE ON SHEAR STRENGTH OF ALLOY (2)(6)

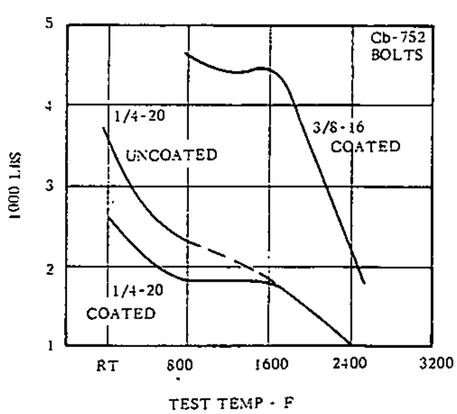


FIG. 3.0317 EFFECT OF ELEVATED TEMPERATURE ON TENSION PROPERTIES OF BOLTS (24)

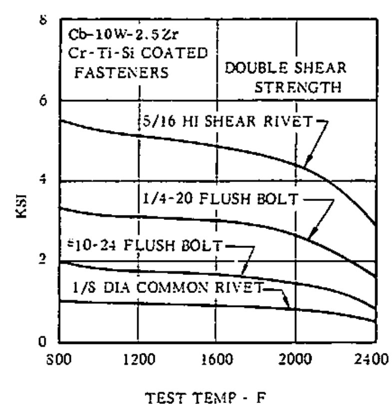


FIG. 3.0352 EFFECT OF ELEVATED TEMPERATURE ON DOUBLE SHEAR STRENGTH OF COATED FASTENERS (24)

	Cb
10	W
2.5	Zr

Cb-752

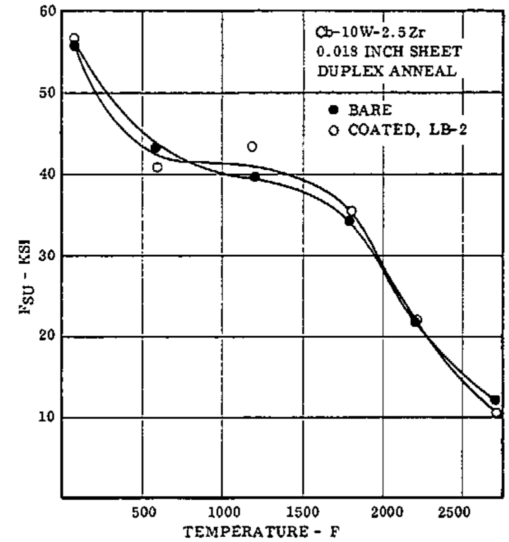


FIG. 3.0353 EFFECT OF ELEVATED TEMPERATURE ON THE SHEAR STRENGTH OF COATED AND UNCOATED SHEET. (4)(16)

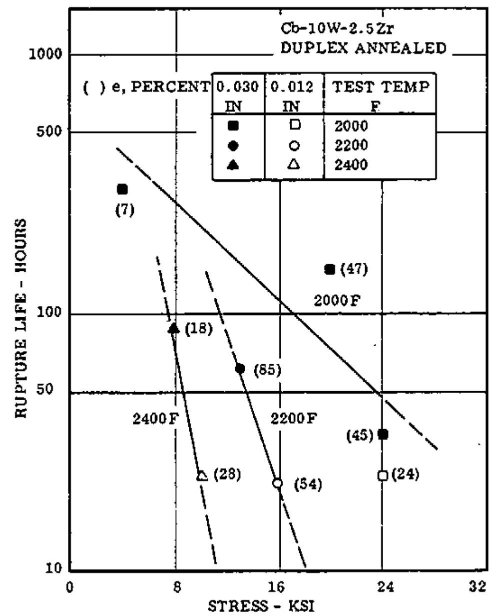


FIG. 3.041 CREEP RUPTURE PROPERTIES OF DUPLEX ANNEALED SHEET. (4)(5)

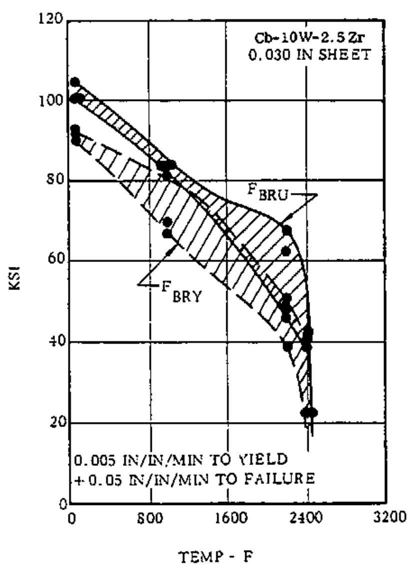


FIG. 3.0361 EFFECT OF ELEVATED TEMPERATURE ON BEARING STRENGTH OF SHEET (2)(6)

Note:
Effective bearing area was taken as product of hole diameter and the thickness of test specimen.

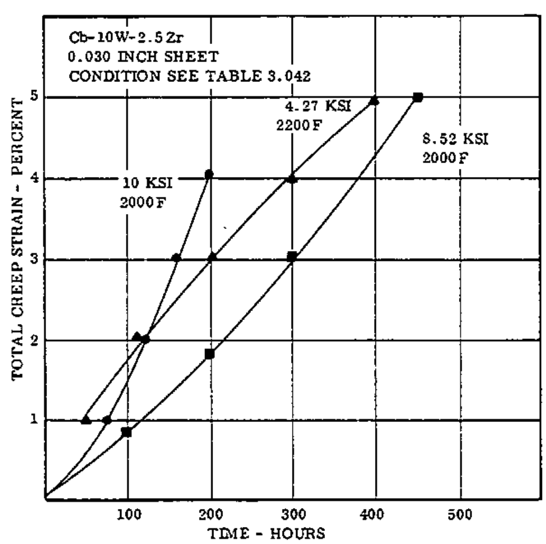


FIG. 3.043 CREEP CURVES FOR SHEET AT 2000 AND 2200F. (7)

	Cb
10	W
2.5	Zr

Cb-752

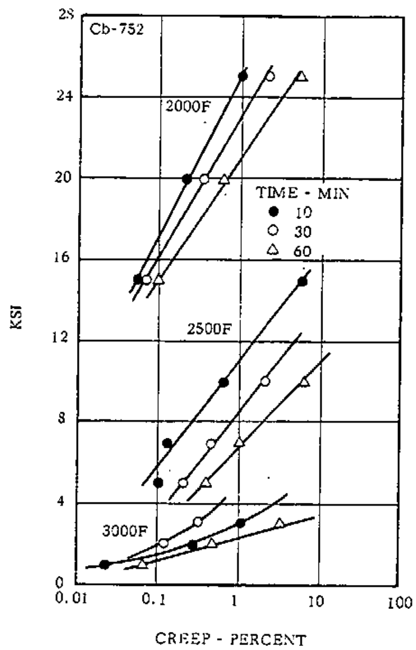


FIG. 3.043 ISOCHRONOUS STRESS-STRAIN CURVES FOR ALLOY (S,p.A-17)

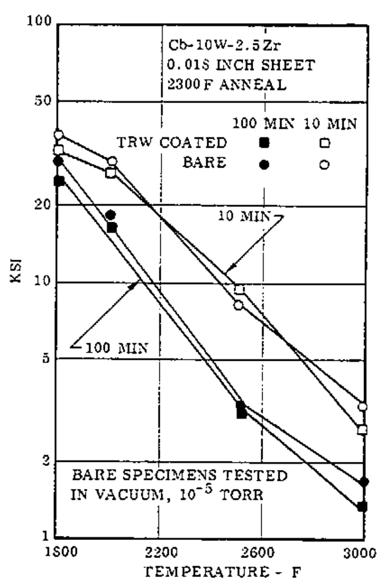


FIG. 3.044 CREEP STRENGTH VERSUS TEMPERATURE FOR BARE AND COATED SHEET FOR 1 PERCENT CREEP. (S)

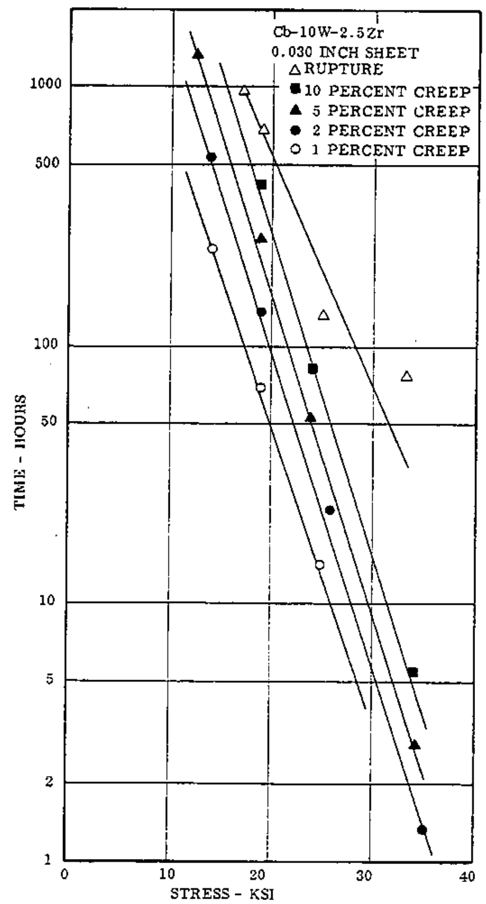


FIG. 3.045 TOTAL CREEP CURVES AT 1800F FOR DUPLEX ANNEALED SHEET. (25)

	Cb
10	W
2.5	Zr

Cb-752

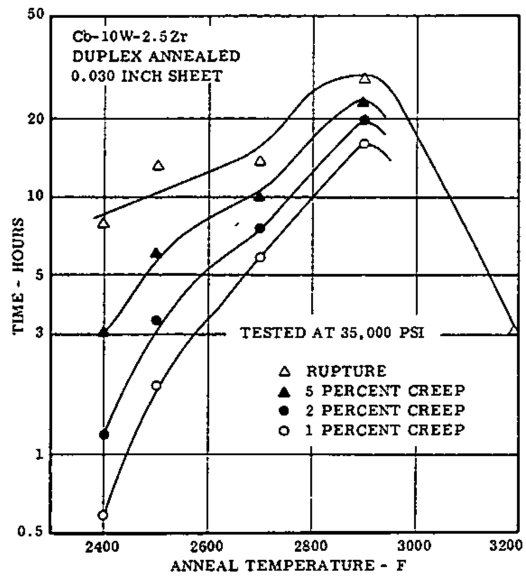


FIG. 3.047 EFFECT OF ANNEALING TEMPERATURE ON THE CREEP PROPERTIES OF SHEET AT 1800F. (25)

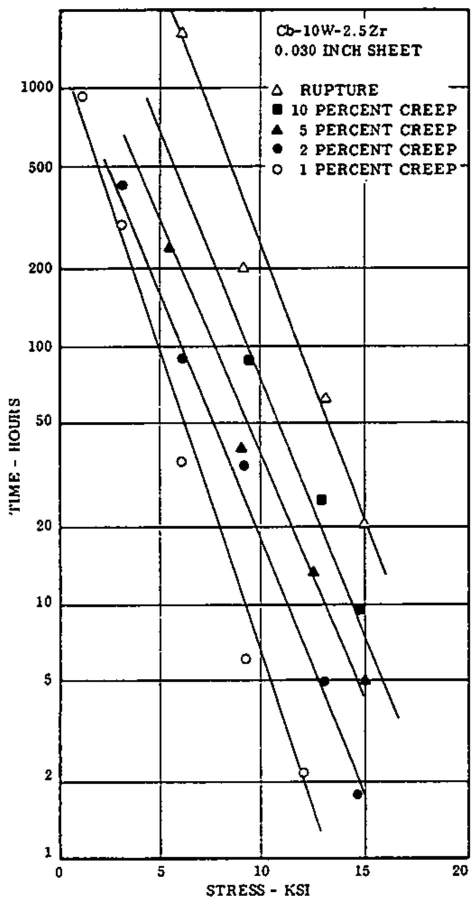


FIG. 3.046 TOTAL CREEP CURVES AT 2200F FOR DUPLEX ANNEALED SHEET. (25)

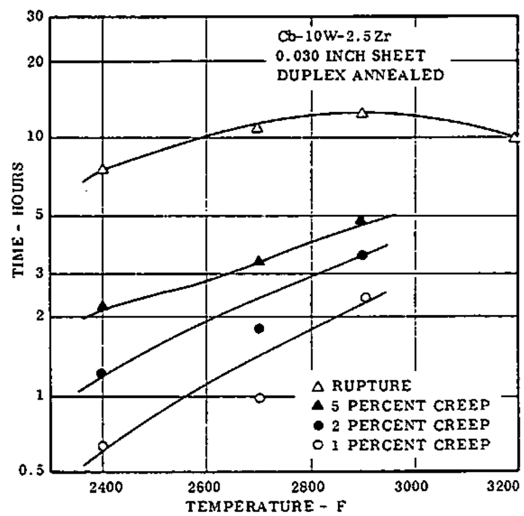


FIG. 3.048 EFFECT OF ANNEALING TEMPERATURE ON THE CREEP PROPERTIES OF SHEET AT 2200F AND 17.5 KSI. (25)

	Cb
10	W
2.5	Zr

Cb-752

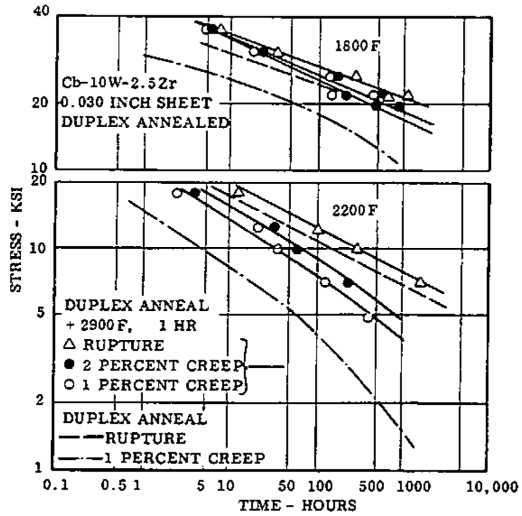


FIG. 3.049 TOTAL CREEP CURVES AT 1800 AND 2200F FOR DUPLEX ANNEALED SHEET TREATED FOR 2900F, 1 HR PRIOR TO TESTING. (25)

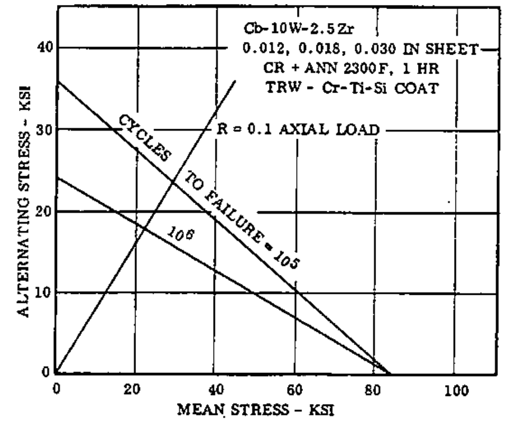


FIG. 3.052 STRESS RANGE DIAGRAM FOR COATED SHEET AT ROOM TEMPERATURE. (8)

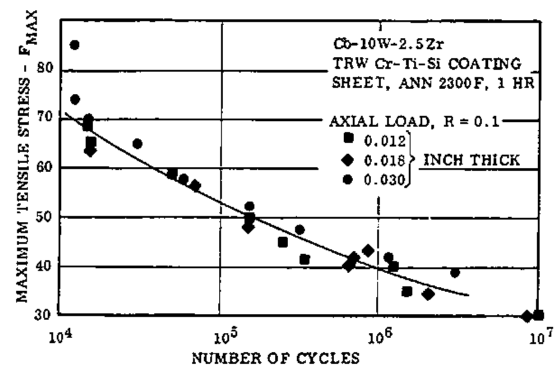


FIG. 3.053 FATIGUE PROPERTIES FOR COATED SHEET AT ROOM TEMPERATURE. (8)

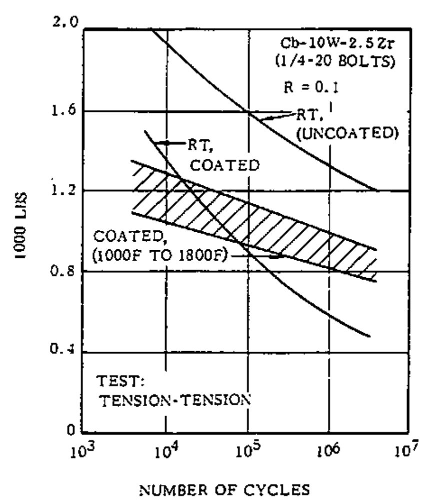


FIG. 3.051 S-N CURVE FOR COATED AND UNCOATED BOLTS AT ROOM TEMPERATURE AND 1000F TO 1800F (26)

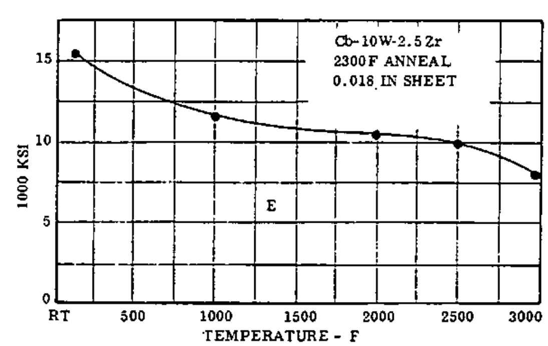


FIG. 3.0621 MODULUS OF ELASTICITY OF SHEET. (8)

	Cb
10	W
2.5	Zr

Cb-752

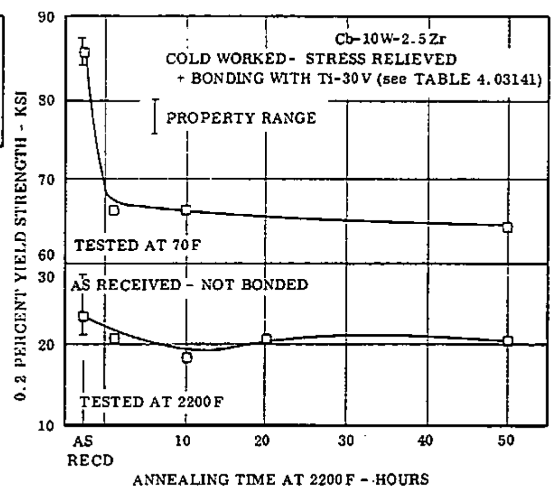


FIG. 4.03142 EFFECT OF ANNEALING TIME ON 70 AND 2200F TENSILE STRENGTH OF 0.020 INCH SHEET BONDED WITH Ti-30V. (23)

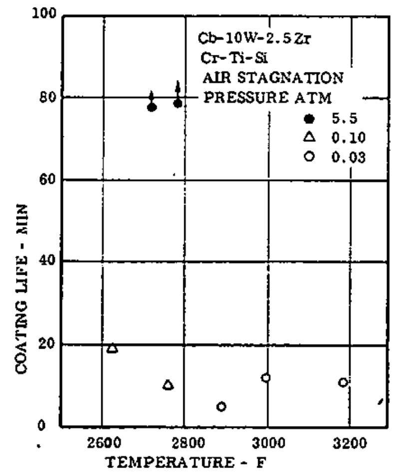


FIG. 4.0522 RESPONSE OF Cr-Ti-Si COATED ROD TO DYNAMICS TEST ENVIRONMENT. (31)

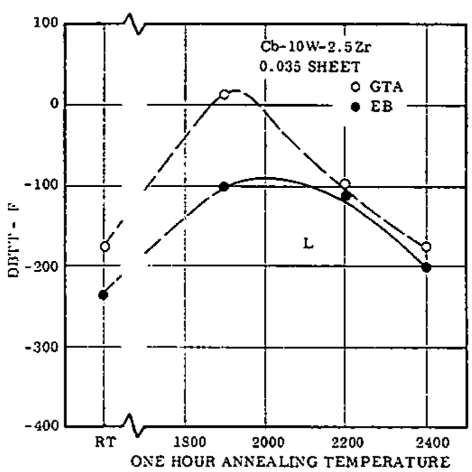


FIG. 4.0323 EFFECT OF ANNEALING ON GTA AND EB WELD BEND DUCTILITY. (28)

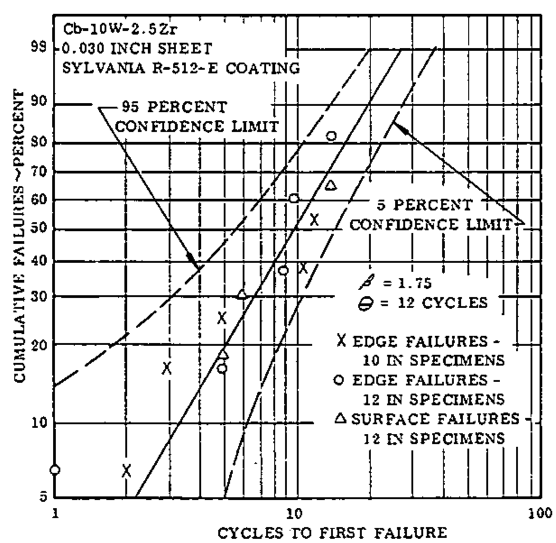


FIG. 4.05231 WEIBULL PLOT OF 2600F CYCLIC OXIDATION TEST RESULTS FOR FUSED SLURRY SILICIDE SYLVANIA COATING (15 MIN SLOW HEAT TO 2600F 1 HR HOLD 15 MIN COOL TO ROOM TEMPERATURE). (32)

	Cb
10	W
2.5	Zr

Cb-752

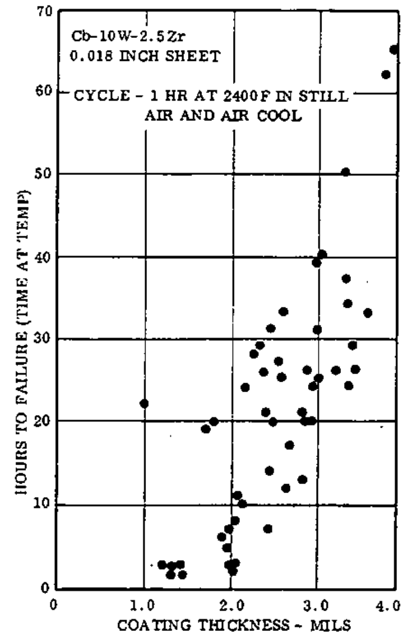


FIG. 4.05241a OXIDATION LIFE AT 2400F VAC HYD (Si-Hf-Cr-Fe) COATED. (32)

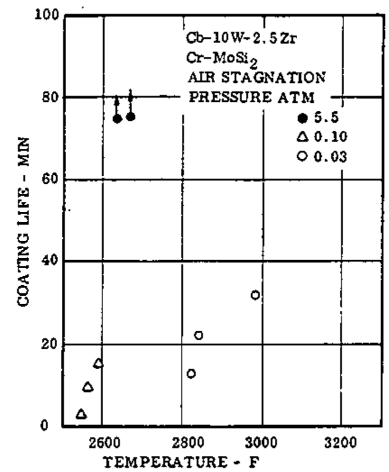


FIG. 4.05243 RESPONSE OF Cr-MoSi$_2$ COATED ROD TO DYNAMIC TEST ENVIRONMENT. (31)

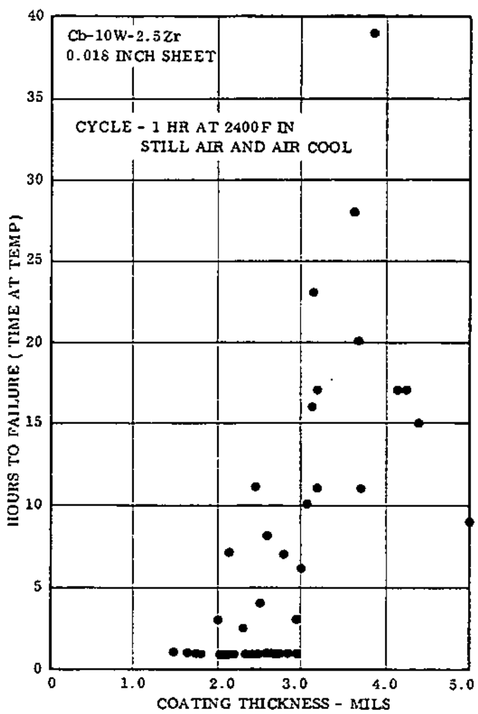


FIG. 4.05241b OXIDATION LIFE AT 2600F VAC HYD (Si-Cr-Hf-Fe) COATED. (32)

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	Cb
10	W
2.5	Zr

Cb-752

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