Ta
8 W
2.4 Hf

T-111

1. GENERAL

This refractory metal alloy was originally designed for short time aerospace applications which required high strength for elevated temperature applications. It now finds wide acceptance as a structural containment material for high temperature liquid metal (Rankine cycle) loops and for isotope systems. It is a highly fabricable alloy and can be processed by all conventional primary and secondary metal working operations. It retains ductility and strength from -320F to 2500F. Availability in all mill forms from the major refractory metal producers is generally good. Both the stress relieved and recrystallized conditions are available depending on end usage requirements. T-111 is classified as a low interstitial alloy; for higher short time and improved creep properties a variation of this alloy, T-222 (10W+2.5Hf+0.01C) is available.

1.01 Commerical Designation
T-111 (Ta-8W-2Hf)

1.02 Alternate Designations
WC-111, Fansteel 111

1.03 Specifications
1.031 AMS specifications - none.
1.032 General Electric 01-0015-01-D (2)
1.033 Westinghouse PDS 30112-1 (3)

1.04 Composition
Table 1.04

TABLE 1.04

Source	Westinghouse(3)		Wah Chang(4)
	Percent		
	Min	Max	Nominal
Tungsten	7.0	9.0	8.0
Columbium	---	0.10	0.10
Molybdenum	---	0.020	0.10
Nickel	---	0.005	----
Iron	---	0.005	0.005
Oxygen	---	0.010	0.015
Carbon	---	0.005	0.005
Nitrogen	---	0.005	0.0075
Hydrogen	---	0.001	0.001
Chromium	---	---	0.02
Cobalt	---	0.005	0.005
Hafnium	1.8	2.4	2.0
Vanadium	---	0.002	0.002
Tantalum	Balance		Balance

1.05 Heat Treatment
1.051 Stress relief. 2000F, 1 hour (vacuum 1 x 10^{-5} torr or less)
1.052 Full recrystallization. 2950 to 3050F, 1 hour (6, 11, and 12) prior to final anneal with 75 percent CW.
1.0521 Effect of annealing temperature and cold work on re-crystallization of alloy, Figure 1.0521.
1.053 Weld heat treatment, see 4.04.

1.06 Hardness
1.061 Effect of annealing on hardness of alloy, Figure 1.061.

1.07 Forms and Conditions Available
Table 1.07

TABLE 1.07

Source	Wah Chang (4) Fansteel (5)			
Alloy	Ta-8W-2Hf			
Form	Diameter-in	Thickness-in	Width-in	Length-in
Ingot	5-12			
Extrusions: Round	6			
Sheet, Bar		2 1/4	7 - 8	
Plate		3/16 - 3/4	16	
		1/8	36	36
Sheet		.011-.062	18.5	Coil
		.015-.062	60	120
		.062-.125	50	50
Foil		.001-.005	12	Coil
		.005-.010	24	Coil
Rod, Bar	1/8 - 5 1/2			
Wire	.010-.062			Coil
Tubing	.080 x .010 wall minimum 1.0 maximum seamless			120

1.08 Melting and Casting Process
1.081 Electron beam melted ingots of a master alloy of Ta and W are alloyed with hafnium through a minimum of two consumable electrode vacuum arc melts.

1.09 Special Considerations
1.091 Heating of T-111 to incandescent temperatures for short times results in atmospheric contamination. Preventative measures must be taken, i.e., wrapping in Ta foil, canning in Mo, heating in vacuum or dry He or A atmosphere.
1.092 Long duration, over 100 hours, creep tests must be conducted in vacuums of 10^{-8} torr or less to avoid contamination.
1.093 Use of hydrogen, nitrogen and carbon monoxide or high dew point atmospheres for heat treating must be avoided.

2. PHYSICAL AND CHEMICAL PROPERTIES
2.01 Thermal Properties
2.011 Melting point. 5400F (6) estimated.
2.012 Phase changes.
2.0121 Time-temperature-transformation diagrams.
2.013 Thermal conductivity, Figure 2.013 (7, 8).
2.014 Thermal expansion, Figure 2.014 (6).
2.015 Specific heat, approximately 0.036 Btu per (lb F) (32F).
2.016 Thermal diffusivity.

2.02 Other Physical Properties
2.021 Density. 0.604 lb per cu in., 16.7 gr per cu cm (6).
2.022 Electrical properties.
2.0221 Electrical resistivity, Figure 2.0221 (6).
2.023 Magnetic properties.
2.024 Emissivity, Figure 2.024 (9).
2.025 Damping capacity.

2.03 Chemical Properties
2.031 T-111, being a gettered alloy (contains hafnium) is considered (18) to have excellent corrosion resistance to potassium (11) up to 2400F for 4000 hours and cesium up to 2500F (6) for 500 hours. It also has demonstrated good resistance to sodium at 1832F for 1000 hours. In these cases the external ambient is a high vacuum (10^{-7}torr) and the alkali metal is low oxygen, containing less than 20 ppm.
2.032 At temperatures above 1200F and for applications in oxidizing atmospheres, T-111 requires a protective coating such as a silicide or the Sylvania Sn-Al coating. For isotropic earth re-entry application a platinum alloy cladding over the tantalum alloy is suggested.

2.033 Inert to most acid reagents.

	Ta
8	W
2.4	Hf

T-111

2.04 Nuclear Properties

2.041 Tantalum ranks low when considered as a cladding or structural material for fast breeder applications in terms of absorption cross sections. Addition of tungsten and hafnium as in T-111 do not improve its desirability in this respect. It also has a low breeding ratio. However, because of its compatibility with most isotopes and fuels it is a candidate for high temperature reactor structures and for isotope systems which use Pu 238.

2.042 Thermal neutron absorption cross section is 21.3 barns per atom (for pure Ta).

2.043 The mechanical and physical properties of tantalum are only slightly affected under an irradiation of 1×10^{19} slow and 5×10^{19} fast neutrons (22). Indications are that T-111 reacts similarly.

3. MECHANICAL PROPERTIES

3.01 Specified Mechanical Properties

3.011 Westinghouse, Table 3.011

TABLE 3.011

Source	(3)
Alloy	Ta-8W-2Hf
Form	Bar and Rod
Condition	Cold Worked, Recrystallized
F_{tu}, ksi	110.0 maximum
F_{ty}, ksi	100.0 maximum
e(4D), percent	20.0 minimum

3.02 Mechanical Properties at Room Temperature

3.021 Tension, see 3.031.

3.0211 Stress-strain diagrams.

3.0212 Room temperature properties of stress relieved and low interstitial grade sheet, Table 3.0212.

TABLE 3.0212

Source	(14, p. 1)	
Alloy	Ta-8W-2Hf	
Form	Sheet	
Condition	Stress relief, 2250F, 3 hrs Low-interstitial grade	
Thickness - inch	0.040	
Direction	L	T
F_{tu}, ksi	112.3	113.7
F_{ty}, ksi	96.0	100.7
e, percent	21.8	17.9

3.022 Compression.

3.0221 Stress-strain diagrams.

3.023 Impact.

3.024 Bending, see 3.034.

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 test temperature on the tensile properties of recrystallized, and recrystallized and welded sheet, Figure 3.0312

3.0313 Effect of test temperature on tensile properties of warm rolled sheet, Figure 3.0313.

3.0314 Effect of test temperature on tensile properties of cold rolled, stress relieved, and cold rolled and recrystallized sheets, Figure 3.0314

3.0315 Effect of test temperature on warm rolled moderate (0.020 percent) interstitial and cold-rolled low (0.007 percent) interstitial sheet, Figure 3.0315.

3.0316 Effect of test temperature on ultimate tensile strength for transverse tensile tests on T-111 welds unaged and aged at elevated temperatures for 5000 and 10,000 hours (11), Table 3.0316.

TABLE 3.0316

Source	(16)					
Alloy	Ta-8W-2Hf					
Form	Recrystallized .035 Sheet					
Condition	GTA Weld + 2400F 1 Hour + 10,000 Hour Age					
		Aging Temperature - F				
Specimen Location	Test Temp F	No Age F_{tu}	1500 F F_{tu}	1800 F F_{tu}	2100 F F_{tu}	2400 F F_{tu}
Parent Metal	1800 F	62 ksi	59 ksi	53 ksi	54 ksi*	55 ksi
Weld	1800 F	58 ksi	55 ksi	50 ksi*	49 ksi	51 ksi
Parent Metal	2100 F	53 ksi	51 ksi	49 ksi*	47 ksi	48 ksi*
Weld	2100 F	49 ksi	49 ksi*	46 ksi	45 ksi	46 ksi
Parent Metal	2400 F	39 ksi	40 ksi	39 ksi	38 ksi*	38 ksi
Weld	2400 F	38 ksi	39 ksi	38 ksi*	35 ksi	36 ksi*

* 5,000 hours at indicated aging temperature

Ta
8 W
2.4 Hf

T-111

3.032 Compression.

3.0321 Stress-strain diagrams.

3.033 Impact.

3.034 Bending.

3.0341 The ductile-brittle transition temperature (dbtt) of 0.035 inch sheet is less than -320F. In the as GTA and electron beam welded condition the dbtt is -250 to -350F (11).

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 <u>Creep and Creep Rupture Properties</u>

3.041 Creep properties for 0.030 inch sheet, Table 3.041.

TABLE 3.041

Source	(13)(14)								
Alloy	Ta-8W-2Hf								
Form	Sheet, 0.030 inch							CR 80 percent to 0.030 inch sheet	
Condition	3000F, 1 hr							2600F, 1 hr	
Temp, F (a)	1800	1860	2000		2120	2200		2000	2200
Stress, ksi	17	20	15	13	12	8	12	15.9	7.9
0.1 percent creep, hrs	1900	500	160	200	400	250	125		
0.5 percent creep, hrs			700		1750	1220	650	200	100
(a) Tests at 10^{-8} torr									

3.042 Creep properties for 0.040 inch sheet, Table 3.042.

TABLE 3.042

Source	(15)												
Alloy	Ta-8W-2Hf												
Form	Sheet, 0.040 inch												
Condition	3000F, 1 hour												
Temp, F (a)	1860	2000	2200			2400					2500		
Stress, ksi	20	20	8	12	21.3	10	12.7	14.1	14.7	15.2	8.3	9.2	12.7
0.5 percent creep, hrs					24		76		27		72	67	
1.0 percent creep, hrs	16700	670	2000	1000	45	300	119	42	42	18	117	93	26
(a) Tests at 10^{-8} torr													

3.05 <u>Fatigue Properties</u>

3.051 Preliminary studies (26) on the elevated temperature fatigue, under combined loading conditions ("A" ratio from 0.11 to 0.45), high vacuum (1×10^{-7} torr) and very high frequency (19000 Hz) indicate an approximate 30,000 psi peak stress limit at 10^{10} cycles and 40,000 psi at 10^8 cycles.

3.0511 Representative fatigue data, Table 3.0511.

TABLE 3.0511

Source	(26)		
Alloy	Ta-8W-2Hf		
Form	Recrystallized Bar		
Condition	3000F, 1 hr		
Test Conditions	19,200 Hz at 2000F (10^{-7} torr) axial loaded, resonant fatigue		
Mean Stress F_{mf}-ksi	A	Test Time hrs	Percent Creep
27.6	0.08	76.7*	8.3
37.2	0.11	3.1*	9.5
28.6	0.14	123.8*	10.9
32.1	0.23	14.8	10.3
27.6	0.27	18.8	10.3
24.8	0.29	39.9	5.3
20.7	0.32	111.8	3.11
15.9	0.36	158.0*	0
32.1	0.42	3.9	15.1
27.6	0.42	5.1	8.4
24.1	0.45	1.8	4.26
*Run-out			

	Ta
8	W
2.4	Hf

T-111

3.06 Elastic Properties

3.061 Poisson's ratio.

3.062 Modulus of elasticity, Figure 3.062.

3.063 Modulus of rigidity.

4. FABRICATION

4.01 Formability

4.011 General.

4.0111 The alloy has very good forming characteristics. It can be blanked, punched or sheared without edge cracking at room temperature. All normal sheet metal forming operations - bending, brake forming, drawing, spinning, can be practiced at room temperature (6).

4.012 Forming.

4.0121 Steel dies can be used for blanking or punching with a clearance between punch and die of 6 percent of sheet thickness. Light oils or chlorinated lubricants should be used.

4.0122 Form stamping processes are similar to those used for mild steel. Dies can be steel, beryllium copper, or aluminum bronze. Low melting die alloys can be used on short runs. Rubber or pneumatic die cushions should be used where required. Annealed T-111 shows little springback.

4.0123 Only annealed T-111 should be used for deep drawing operations. If the piece is to be drawn in one operation, a draw in which the depth is equal to the diameter of the blank can be made. If more than one drawing operation is to be performed, the first draw should have a depth of not more than 40 to 50 percent of the diameter. Dies should be aluminum bronze with a steel punch. Chlorinated or sulfonated oil is a suitable lubricant.

4.013 Extruding.

4.0131 Extrusion of T-111 is readily accomplished. Ingots up to 9.5 inches have been extruded by canning in mild steel cans at 2300F. An extrusion constant of 40 to 44 tsi is developed.

4.014 Forging.

4.0141 T-111 forges readily at 2200F. To prevent contamination the billets are coated with an Al-Si alloy. Billets forged with this practice have shown slight C pickup and O_2 or N_2 after a total of 8 hours at 2200F during the forging cycle.

4.015 Drawing.

4.0151 Ingots are extruded into tube blanks or solid billets which are bored to form tube blanks. Rocking is accomplished at room temperature. Final drawing of the tubes typically reduces the OD from 0.375 to 0.250 inch and wall thickness from 0.662 to 0.615 inch. Tensile properties of finished tubes is comparable to flat-rolled sheet products (20).

4.02 Machining and Grinding

4.021 Cemented carbide tools with cutting speeds in the order of 100 sfm will produce good results in single point turning operations. Slow speeds will cause tearing. The following conditions are recommended for single point tools:

10°	back rake
5°	side rake
5°	side clearance
45°	trail angle
0.020"	nose radius

4.022 Milling cutters should be of the staggered tooth type, using good back and side relief.

4.023 In drilling, the point of the drill should be relieved so that it does not rub the work.

4.024 In threading larger diameters, it is preferable to cut the threads on a lathe rather than with a threading die; when dies or taps are used, they must be kept free of chips and cleaned frequently. Extremely light finishing cuts should be avoided.

4.025 Grinding of T-111 is difficult and should be avoided if possible. Grade 38A-60 wheels or equivalent can be used.

4.026 Electropolishing of T-111 can be accomplished in a solution of 9:1 H_2SO_4/HF.

4.03 Welding

4.031 General. GTA, electron beam and resistance welding processes can be used to join this alloy to itself and to other tantalum and columbium base alloys (6, 16). Extreme care must be taken to avoid contamination as contaminants will cause weld ductility to decrease rapidly. A vacuum purged weld-box, backfilled with high purity He and/or A ($<$ 5 ppm H_2O, $<$ 5 ppm O_2) achieves the best results. Helium is the preferred inert gas. The weld-box should be capable of 5×10^{-6} torr and $< 3 \times 10^{-5}$ torr per minute leak rate to produce contamination free welds (2). Foil, sheet and plate welding have been accomplished satisfactorily (22).

4.032 Effect of temperature on minimum bend radius, Table 4.032.

TABLE 4.032

Source	(6)	
Alloy	Ta-8W-2Hf	
Form	Sheet	
Condition	Stress Relieved 2000F, 1 hr	As Welded*
Thickness, inch	0.040	
Bend Test	Minimum Bend Radius	
Temp, F	Base Metal	Welded Metal
78	0t	1.3t
-200	--	2.0t
* No post heat treatment, grinding or preparation of weld. Punch speed : 1 inch per minute.		

4.0321 Using GTA at 15 ipm and 115 amps, T-111 sheet (0.035M), when given a 2400F postweld anneal, exhibits a 1T bend at $<$ -320F in both the longitudinal and transverse direction (23).

4.033 Tensile property data on transverse butt weldments in 6 mil foil (21), Table 4.033.

TABLE 4.033

Source	(21)					
Alloy	Ta-8W-2Hf					
Form	Foil, 0.006 inch, cold rolled and recrystallized					
Condition	Parent Metal		GTA Weld		Electron Beam	
Test Temp, F	75	2000	75	2000	75	2000
F_{tu}, ksi	101	66.2	94.2	65.1	95.3	57.5
F_{ty}, ksi	90.3	39.7	82.3	43.2	86.6	39
e(1 inch), %	32	17.5	11.5*	7.0*	5.0*	6.0*
*Failed in edge of weld.						

4.034 Tensile behavior of welds in oxygen contaminated T-111 has been explored between 70 and 1000 ppm of oxygen at temperatures up to 2200F. Increasing the oxygen content increased the strength and reduced the ductility with the effect being smallest at the highest temperature, Table 4.034.

TABLE 4.034

Source	(16)											
Alloy	Ta-8W-2Hf											
Form	Sheet, 0.035 inch											
Condition	Cold rolled and recrystallized											
Temperature, F	RT			1500			1800			2200		
Nominal O_2 Level, percent(a)	0.004	0.022	0.080	0.004	0.021	0.081	0.004	0.023	0.081	0.004	0.021	0.081
F_{tu}, ksi	86.6	96.0	94.1	64.0	70.7	72.8	57.3	66.3	58.1	42.4	44.3	48.9
F_{ty}, ksi	75.3	85.3	87.6	38.8	44.0	56.5	33.9	43.5	----	29.0	31.8	41.5
e(1 inch), percent	19.5	9.0	2.0	14.0	13.0	5.0	15.0	9.0	----	24.0	22.0	16.0
Fracture Location	Base	HAZ	HAZ	Base	Base	Base	Base	HAZ	*	Base	Base	Weld
*Failed in griphold												

(a) Based on weight gain following 50 hours diffusion anneal at test temperature in an oxygen contaminated atmosphere. Room temperature specimens treated at 1800F.

4.035 Tensile tests on welded T-111, Table 4.035.

TABLE 4.035

Source	(24)					
Alloy	Ta-8W-2Hf					
Form	Sheet, 0.035 inch					
Condition	96 percent CR + 2400F, 4 hrs (ASTM grain size number 9) + GTA weld(a) + 2400F, 1 hr					
Temp, F	1800		2100		2400	
Location	Parent	Weld	Parent	Weld	Parent	Weld
F_{tu}, ksi	62	58	53	49	39	38
F_{ty}, ksi	35	32	29	30	23	24
e(1 inch), percent	14	10.5	20	14	31	11

(a) 15 ipm, 115 amps, 3/8 inch clamp spacing

4.036 Plate welding.

4.0361 Evaluation of 0.375 inch plate welded by manual GTA indicates good weldability and strength (F_{tu} = 96 ksi L and 86 ksi T) after postweld anneal of 2400F, 1 hour. In the as-welded condition 3T bend tests showed 140° deformation in the longitudinal direction and 120° deformation in the transverse direction, both with some tensile tearing. After postweld anneal 3T bends 135° to 140° could be made in either direction (23).

4.037 Brazing.

4.0371 Vacuum brazing with Cu or Cu -40 percent Au (maximum) be used for low temperature applications.

4.04 <u>Heat Treatment</u>

4.041 All heat treatments of T-111 should be accomplished in vacuums of 1 x 10^{-5} torr or better with equipment that has a < 5 x 10^{-5} torr per minimum leak rate or better, to avoid harmful contamination. Conservative practice calls for wrapping the article being heat treated in Ta foil.

4.042 Annealing is accomplished at temperatures above 2500F and varies with the hardware, with 3000F recommended.

4.043 Postweld heat treatment is accomplished at 2400F for 1 hour.

4.044 To completely homogenize the solute re-distribution produced by fusion welding, a 4000F solution anneal is effective.

4.05 <u>Surface Treatment</u>

4.051 Pickling can be accomplished in a reagent composed of 20 - 35 percent HF, 0-10 percent H_2SO_4, 20 - 35 percent HNO_3, 30 - 50 percent H_2O at temperatures up to 140F.

4.052 Coating.

4.0521 To achieve oxidation resistance at elevated temperatures, T-111 must be coated with a layer of another material which has oxidation resistance and which will not reduce the properties of the base metal during service. Coatings can be devided into three classes: intermetallics, metallics and ceramic.

4.0522 Intermetallics include application of silicides by pack-cementation techniques. The most effective coatings were Si + B, Si + Mn, and Si + V. "Pest" reaction is prevalent with this class. Aluminides and beryllides have been evaluated with a Sn-Al-Mo base slurry developed to commercial scale. More recently a complex Ti, Mo, W, V modified silicide coating has achieved protection for hundreds of hours at 1600F and 2400F. For high temperature, 3000F, short time protection, a Si-20Ti-1Mo is being considered.

4.05221 Foil coated with a Si-Al and exposed to a complex temperature profile with a maximum of 2700F degraded both fatigue and notched tensile severely (25).

4.0523 Metallic coatings using hafnium base alloys and precious metals are being evaluated; specifically, the binary Hf-Ta alloy and Ir base alloy as cladding to T-111 are being considered. The Hf-Ta alloys show promise.

4.0524 Ceramics in the form of bulk HfO_2 have been considered for specific applications, i.e. re-entry.

	Ta
8	W
2.4	Hf

T-111

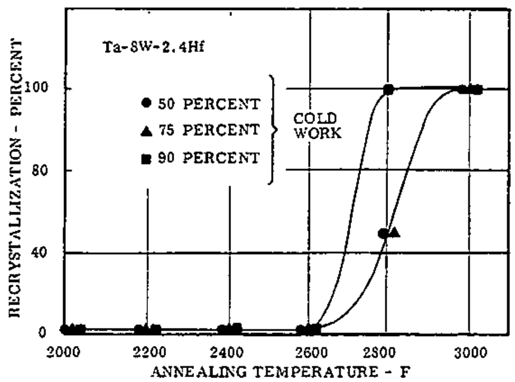

FIG. 1.0521 EFFECT OF ANNEALING TEMPERATURE AND COLD WORK ON RECRYSTALLIZATION OF ALLOY (6, p. 2)

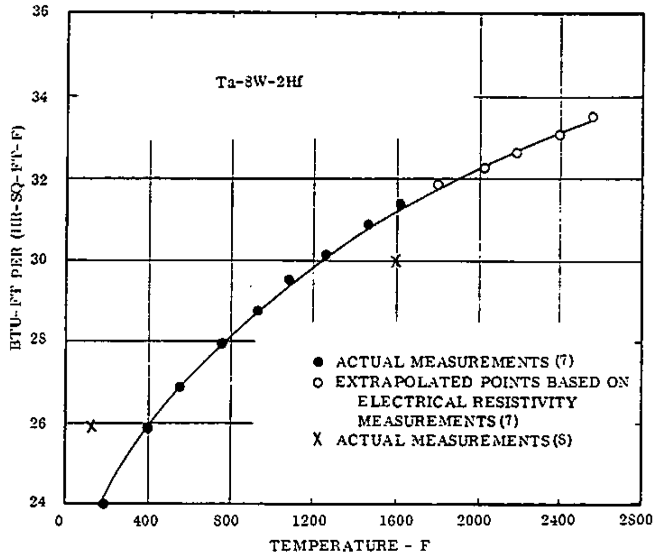

FIG. 2.013 THERMAL CONDUCTIVITY (7)(8)

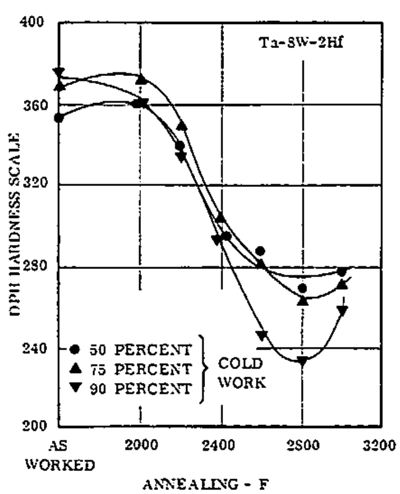

FIG. 1.061 EFFECT OF ANNEALING ON HARDNESS OF ALLOY (6, p.2)

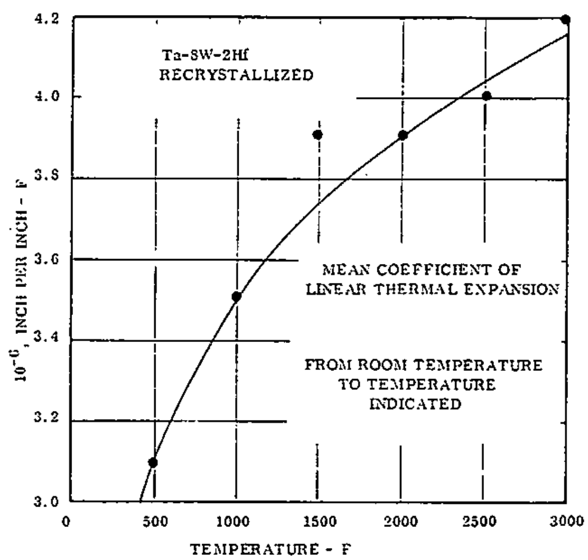

FIG. 2.014 THERMAL EXPANSION (6)

Ta
8 W
2.4 Hf

T-111

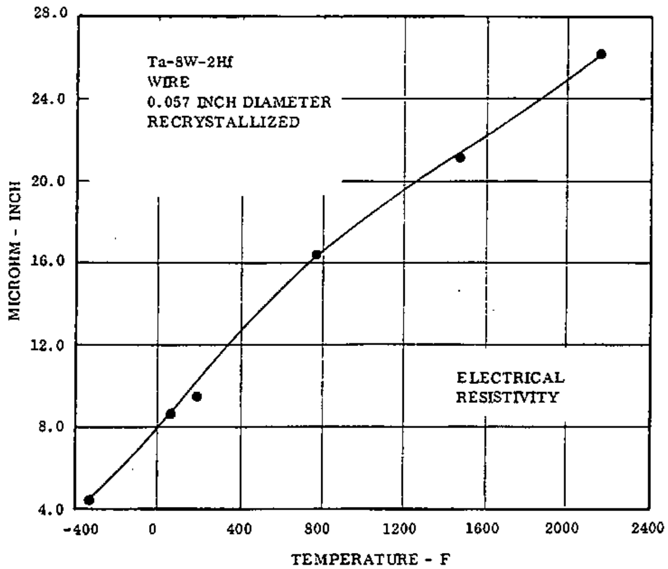

FIG. 2.0221 ELECTRICAL RESISTIVITY (6)

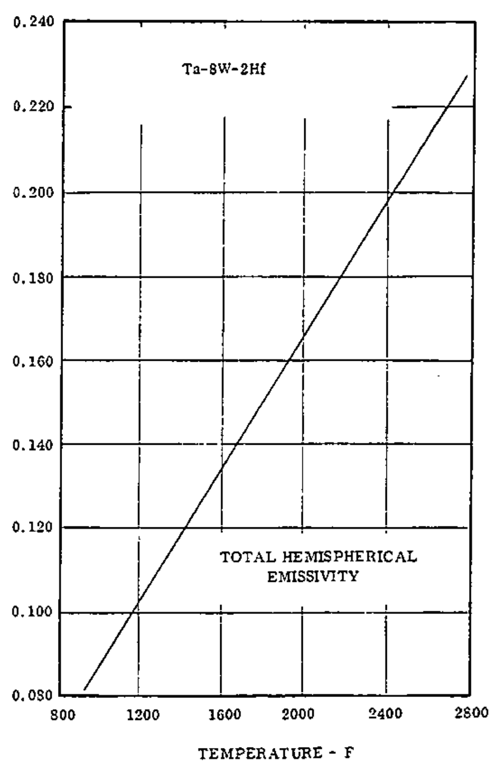

FIG. 2.024 EMISSIVITY (9)

Ta
8 W
2.4 Hf

T-111

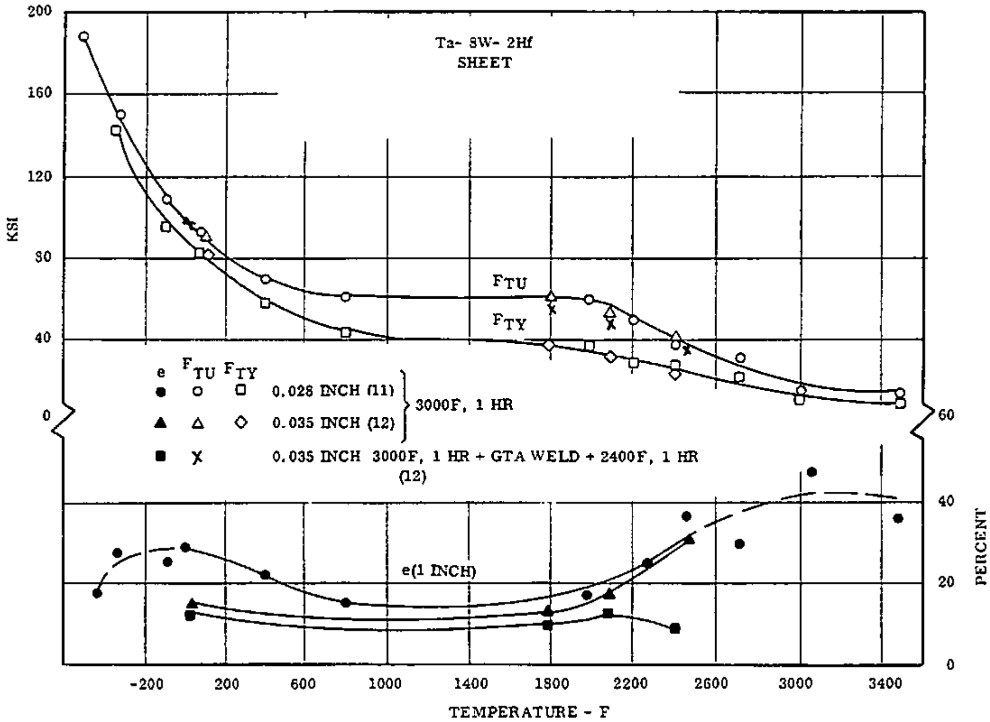

FIG. 3.0312 EFFECT OF TEST TEMPERATURE ON THE TENSILE PROPERTIES OF RECRYSTALLIZED AND WELDED SHEET (11)(12)

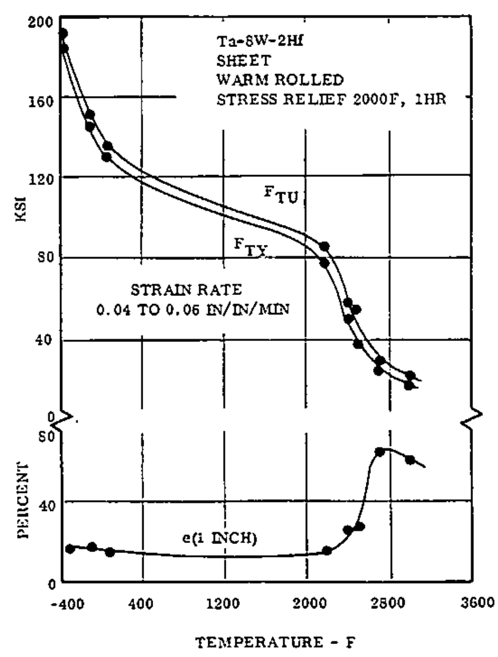

FIG. 3.0313 EFFECT OF TEST TEMPERATURES ON TENSILE PROPERTIES OF WARM ROLLED SHEET (5, p.1)

Ta
8 W
2.4 Hf

T-111

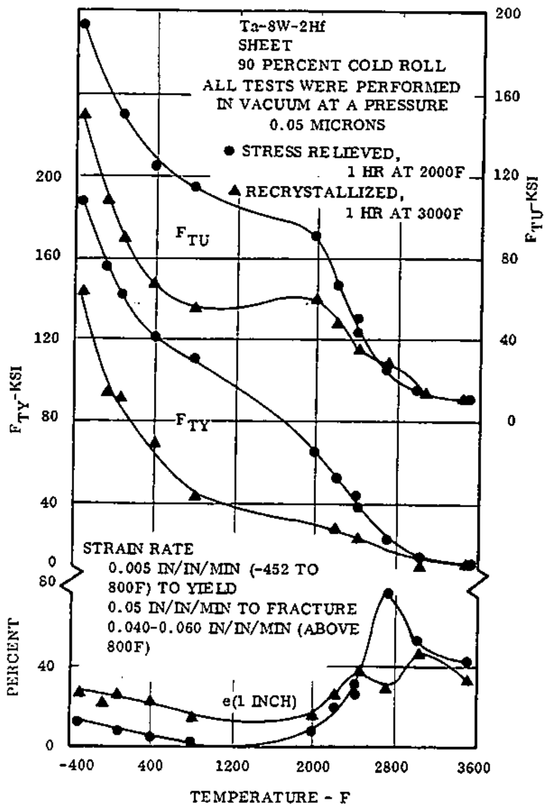

FIG. 3.0314 EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF COLD ROLLED STRESS RELIEVED AND COLD ROLLED RECRYSTALLIZED SHEETS*
(6, p. 1)

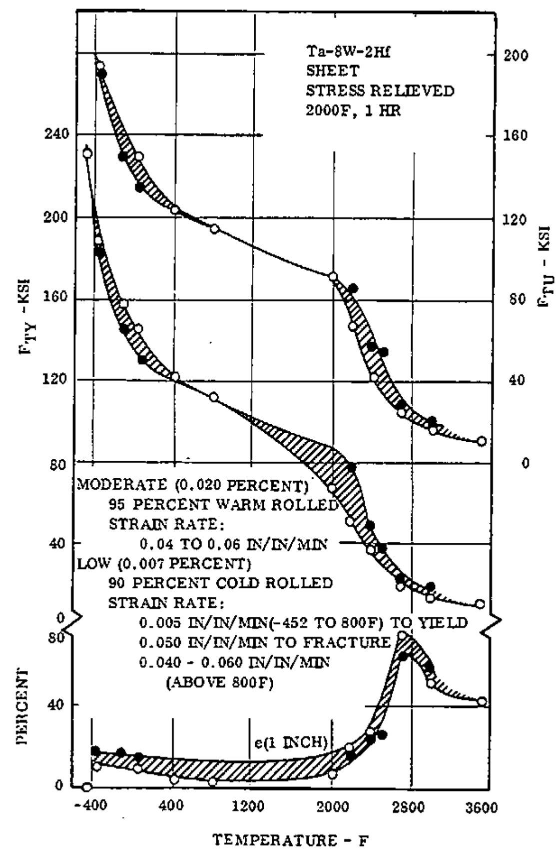

FIG. 3.0315 EFFECT OF TEST TEMPERATURE ON WARM ROLLED, MODERATE (0.020 PERCENT) INTERSTITIAL AND COLD ROLLED LOW (0.007 PERCENT) INTERSTITIAL SHEET
(19, Table 1)

Ta
8 W
2.4 Hf

T-111

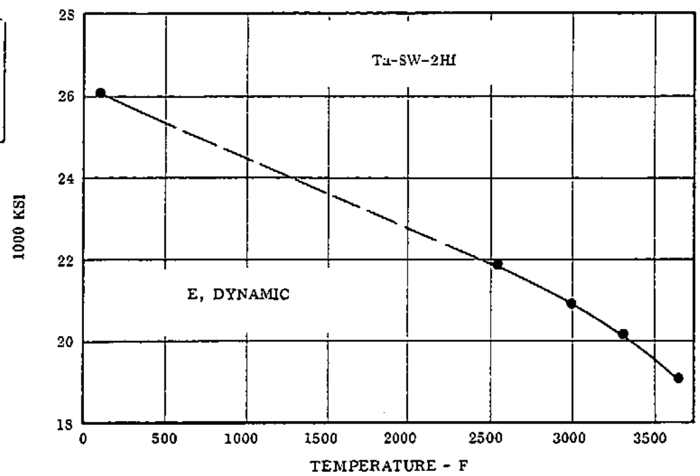

FIG. 3.062 MODULUS OF ELASTICITY (10)

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1. General Electric Specification 01-0040-01-D
2. General Electric Specification 01-0015-01-D
3. Westinghouse PDS 30112-1
4. Wah Chang
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