1\. GENERAL
Tungsten is particularly attractive for high temperature applications as indicated by its extremely high melting point and high modulus of elasticity. Utilization of this metal, however, has been restricted by its high ductile-brittle transition temperature, its poor oxidation resistance and high density.

1.01 Commercial Designation. Tungsten, comm. pure.

1.02 Alternate Designation. None.

1.03 Specifications. None.

1.04 Composition. Table 1.04.

1.09 Special Considerations
All sintering, melting, heating and welding must be done in vacuum, hydrogen or in an inert gas, (18, p.14).

2\. PHYSICAL AND CHEMICAL PROPERTIES

2.01 Thermal Properties
2.011 Melting point. 6170 F.
2.012 Phase changes. None.
2.013 Thermal conductivity, Fig. 2.013.
2.014 Thermal expansion, Fig. 2.014.
2.015 Specific heat, Fig. 2.015.

2.02 Other Physical Properties
2.021 Density. 0.697 lb per cu in. 19.3 gr per cu cm.
2.022 Specific resistance, Fig. 2.022.

TABLE 1.04

Source	GE (9)		Pansteel Metall. (17, p. 47)	
Form	Powder	Rod	Powder	Rod, sheet, wire
	Percent Nominal	Percent Nominal	Percent Nominal	Percent Nominal
Aluminum	< 0.001	-	0.001	0.001
Carbon	0.001-0.002	0.007	0.005-0.01	0.005-0.01
Chromium	< 0.001	-	-	-
Copper	< 0.001	-	< 0.01	-
Iron	0.001-0.002	0.001	< 0.01	0.002
Magnesium	< 0.001	-	-	0.001
Manganese	< 0.001	-	< 0.01	-
Molybdenum	0.005-0.02	0.004	0.007	0.007
Nickel	< 0.001	-	0.006	0.006
Silicon	< 0.001	0.002	0.01	0.01
Oxygen-Nitrogen	0.031	-	0.05	-
Hydrogen	-	0.00001	-	-
Oxygen	-	0.0003	-	0.004
Nitrogen	-	0.00003	-	-
Potassium	0.001	0.004	-	-
Sodium	< 0.001	0.002	-	-
Calcium	< 0.001	0.001	0.01	-
Tin	< 0.001	-	-	-
Ruthenium	-	-	0.01	-
Tungsten	Balance	Balance	Balance	Balance

1.05 Heat Treatment
1.051 Stress relief. 1830 F, 20 to 30 min, depending upon the thickness, (8, p.106). Has been stress relieved at 1830 F, 3 hr, without recrystallization, (9, p.3).
1.052 Anneal. Swaged rod annealed at 2900 F, 3 hr, causes recrystallization, (9, p.3).
1.053 Ingots extruded at 3000 F, forged and rolled at lower temperatures, (see 1.08). Recrystallization temperature after 60 percent reduction by rolling is 1 hr at 2280 F, (7, p.363).

1.06 Hardenability

1.07 Forms and Conditions Available

1.08 Melting and Casting Practice
Commercially pure Tungsten is prepared by either vacuum or H_2 sintering of purified Tungsten powder. Sintered rod is used either directly for preparation of wrought products or as electrode for arc melting, (consumable or non-consumable). Better results are obtained with reverse polarity (electrode positive) than with straight polarity (electrode negative),(11). Purification and increased consolidation is achieved by zone refining using induction or electron beam furnace. Reported impurity levels of N_2, O_2 and H_2 less than 1 ppm for 4 inch consumable electrode arc melted ingot are better than limit of measurement capability, (7, p. 363).

2.03 Chemical Properties

W, COMM PURE 2.031 Corrosion resistance, Table 2.031.

TABLE 2.031

Source	(6, p.14)
Corrosive	Behaviour
Hydrochloric acid, sulphuric acid or nitric acid	Cold, dilute or concentrated: practically insoluble Warm, dilute or concentrated: slight attack
Aqua regia	Cold: practically insoluble Warm: rapid attack
Hydrofluoric acid	Cold or warm: insoluble
Hydrofluoric and nitric acid mixed	Rapid attack
Alkalies	Cold aqueous caustic soda or potash: practically insoluble. Molten caustic soda or potash or alkaline carbonates: a) in air: slow oxidation b) in the presence of oxidizing agents, e.g. KNO_3, KNO_2, $KClO_3$, PbO_2: rapid solution
Ammonia	Practically insoluble to attack by aqueous solution, slight attack in the presence of H_2O_2
Sodium nitrite	Molten: rapid solution above 300 C (570 F)
Carbon (lampblack, graphite, charcoal) and hydrocarbons	Formation of carbides from 1400 C (2550 F) complete carburization to WC at 1400 to 1600 C (2550 to 2900 F)
Sulfur	Molten or boiling: slow attack
Mercury and mercury vapour	Practically insoluble
Aluminum oxide, magnesium oxide	Reduction to metal in contact with tungsten above 1900 C (3450 F)
Thorium oxide	Reduction to metal in contact with tungsten above 2200 C (4000 F)
Air and oxygen	Insoluble at room temperature; oxidation starts from 400 to 500 C (750 to 930 F); at temperatures above this rapid oxidation to WO_3 and vaporization
Water	Insoluble at all temperatures
Water vapour	At red heat rapid oxidation to WO_3
Hydrogen	No reaction up to melting point
Nitrogen	No reaction up to highest temperatures
Ammonia	Slight formation of nitrides with powder from 700 C (1290 F). Nitrides dissociate above this temperature.
Carbon monoxide	Carburation begins at 800 C (1470 F)
Carbon dioxide	Oxidation above 1200 C (2190 F)
Halogens	Fluorine: attack at normal temperatures. Chlorine: attack at 250 C (480 F) Bromine and iodine: attack at light red heat
Hydrogen chloride gas	Up to 600 C (1110 F) no attack if free of oxygen
Nitric oxide	Oxidation to WO_3 at high temperatures
Hydrogen sulphide	Surface attack at red heat
Sulfur dioxide	Oxidation at high temperatures
Carbon disulphide	Attack at red heat

2.032 Oxidation resistance. At ordinary temperatures it is unaffected by oxygen but oxidation begins at appreciable rates at 750 F, (8).

3. MECHANICAL PROPERTIES

3.01 Specified Mechanical Properties

3.02 Mechanical Properties at Room Temperature
Sintered bar, 18 ksi. Swaged bar 50 to 213 ksi, wire as a function of diameter, (6, p.6).

3.021 Producer's mechanical properties, Table 3.021.

TABLE 3.021

Source	(9, p.6) (16)			
Metal	W, comm. pure			
Condition	CW	Stress relief	Recrys	Swaged and Ann 3 hr, 1830 F
F_{tu}, min-ksi	180	150	90	215*
max-ksi	200	170	110	
F_{ty}, min-ksi	160	130	80	
max-ksi	180	150	100	
e(1 in)percent	-	-	-	0.2
Hardness				
VHN-min	450	420	280	
max	-	440	310	

*Single test

3.022 Effect of diameter on tensile strength of drawn wire, Fig. 3.022.

3.03 Mechanical Properties at Various Temperatures

3.031 Short time tension properties

3.0311 Effect of test temperature on tensile properties of as-received and recrystallized bar, Fig. 3.0311.

3.0312 Effect of test temperature on drawn Tungsten wire, Fig. 3.0312.

3.0313 Effect of test temperature on tensile properties of swaged rod, Fig. 3.0313.

3.0314 Stress strain curves for recrystallized swaged rod, Fig. 3.0314.

3.032 Short time properties other than tension

3.033 Static stress concentration effects

3.0331 Effect of test temperature on tensile strength of notched and unnotched recrystallized bar, Fig. 3.0331.

3.0332 Effect of test temperature on notched and unnotched stress relieved bar, Fig. 3.0332.

3.04 Creep and Creep Rupture Properties

3.041 Total strain and rupture curves for high purity Tungsten at 2200 and 2500 F, Fig. 3.041.

3.042 Creep rupture curves for recrystallized bar at 1600 to 2200 F, Fig. 3.042.

3.05 Fatigue Properties

3.06 Elastic Properties

3.061 Modulus of elasticity at various temperatures, Fig. 3.061.

3.0611 Modulus of elasticity at room temperature, 59×10^6 psi; 1830 F, 47×10^6 psi, (6, p.6)

4. FABRICATION

4.01 Forming

4.011 Sharp tools are necessary for cutting sheet. The material must be between 750 and 1800 F depending on its thickness. Sheet can be bent at 1500 to 1800 F. Rods are cut with thin organically bonded silicon carbide wheels, water cooled. Thick rod can only be bent at red heat. Electrolytically polished rods up to .12 in diameter can, however, be bent cold, (6, p.30). The ductility of the metal at low temperature is low. Only wire 0.030 in can be cold formed in simple operations. At 200 F, sheet and wire up to 0.010 in can be formed in general operations. Heavier sections than 0.040 in should be heated to 2100 to 3000 F in an inert atmosphere, (8, p.105).

4.012 Blanking, punching and shearing operations should be performed under the limitations mentioned in 4.011. Although tool steel dies can be used, carbide dies are preferable, (8, p.106).

4.013 Hot material can be swaged with limited reduction in each operation. Reheating between operations is necessary, (8, p.106).

4.02 Machining
General. Turning, milling and drilling can be accomplished with considerable difficulty. The hard metal tools with a top rake of 20 to 25° and the clearance 5 to 8° should be used. Recommended cutting conditions, (6, p.31): Speed, 6 to 10 ft/min; feed, 0.0004 to 0.0006 in; depth, 0.02 to 0.04 in.

4.021 Grinding. Shaped pieces can best be produced by grinding, (6, p.31). Care and adequate cooling are necessary to prevent chipping or cracking. Silicon carbide wheels of grain size 100 to 120 are satisfactory for most grinding operations.

4.022 Shearing or punching should be performed on heated materials for sections in excess of 0.040 in, (see 4.011). Sheet in excess of 0.050 in should be sheared to within 1/8 or 1/16 in of desired dimension and edge ground to size, (8, p.106).

4.03 Welding
Tungsten welded to itself by most conventional welding procedures results in an embrittled joint. Only spot welding and inert arc, or hydrogen welding are recommended. Higher melting point metals which do not form brittle intermediate phases with Tungsten have been successfully spotwelded to Tungsten as shown in Table 4.03.

TABLE 4.03

Source	(5, p.46)
Spot welding of tungsten sheet with	Resistance of weld to twisting
Tantalum	Moderate to good
Molybdenum	Brittle (recrystallization)
Columbium	Good
Titanium	Good
Iron	Good
Nickel	Good
Copper	Poor
Aluminum	Poor
Zinc	No weld

4.031 Brazing. Low melting brazing materials are rarely used to join Tungsten due to their low strengths at elevated temperatures. Metals that have been used in brazing Tungsten: Columbium, 83Au-17Ni, Platinum, 75Cu-25Ni and Nickel. Alloying does not appear to be a prerequisite for brazing as copper forms a good bond with Tungsten and is insoluble in Tungsten. Inert or hydrogen atmosphere must always be used, (5, p.45).

4.04 Heating and Heat Treating

4.041 Stress relief annealing can be done at 1830 F, 30 min. Hydrogen firing at 1470 to 1830 F, 10 to 30 min, reduces oxide and relieves stresses. Full annealing involving recrystallization embrittles material. See 1.05, 1.052, (8, p.106).

4.05 Surface Treatment

4.051 Cleaning. Preceded by degreasing, the metal can be cleaned by conventional methods. For parts which have been cold or hot formed in a reducing atmosphere conventional methods are recommended. After heating in air, the oxide coat can be removed by electrolytic caustic cleaning or by immersion in molten caustic soda for a few seconds and rinsed carefully with hot water, (8, p.106).

4.052 The following cleaning methods prior to degreasing are recommended:
1. Immersion in molten sodium hydroxide.
2. Immersion in a molten bath of sodium hydride (operating temperature up to about 1100 F).
3. Electrolize for 30 sec or longer in a 20 percent potassium hydroxide solution, using a 7.5 volt, 200 watt transformer with a Variac in primary, and a carbon electrode.
4. Boil 5 min in 20 percent potassium hydroxide solution.
5. Last traces of oxide may be eliminated by heating in a hydrogen atmosphere at about 1832 F for 15 to 30 min, (5, p.48).

4.053 Polishing. Electrolytical polishing achieves a bright finish by the use of 10 percent solution of sodium hydroxide, (8, p.107).

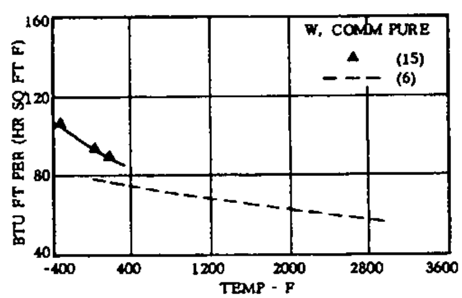

FIG. 2.013 THERMAL CONDUCTIVITY
(6, p.11) (15, p.N-1)

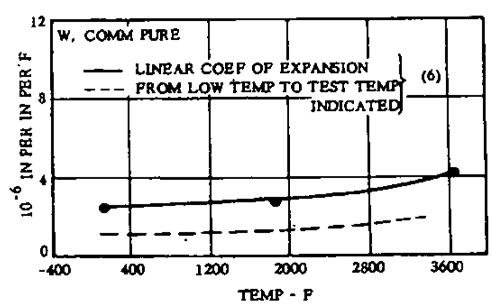

FIG. 2.014 THERMAL EXPANSION
(6, p.7,11)

W, COMM PURE

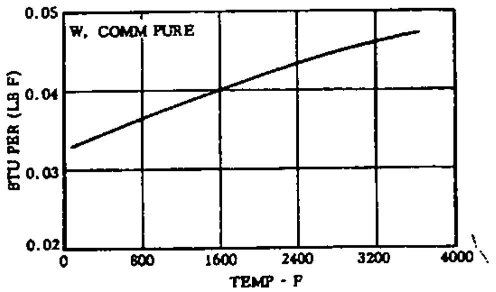

FIG. 2.015 SPECIFIC HEAT (6, p.10)

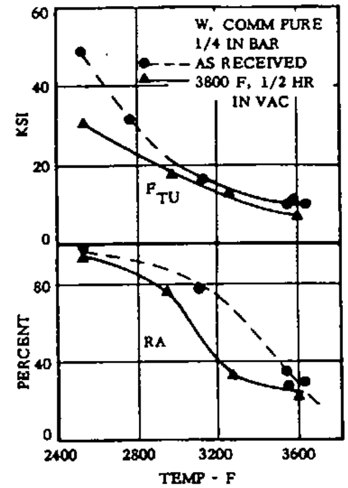

FIG. 3.0311 EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF AS-RECEIVED AND RECRYSTALLIZED BAR (12, p.15)

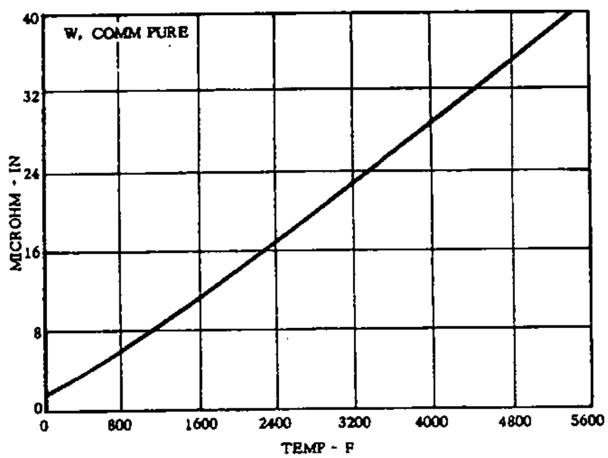

FIG. 2.022 SPECIFIC RESISTANCE (6, p.12)

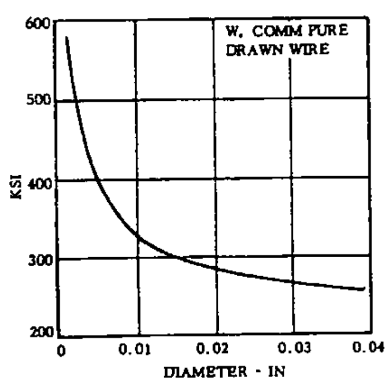

FIG. 3.022 EFFECT OF DIAMETER ON TENSILE STRENGTH OF DRAWN WIRE (6, p.9)

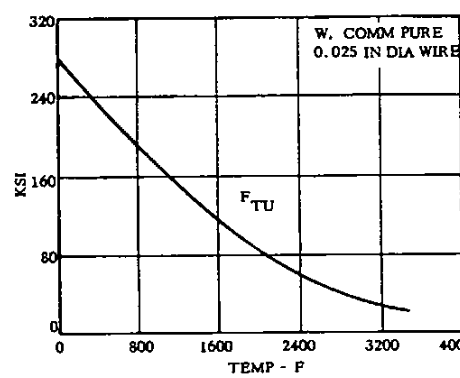

FIG. 3.0312 EFFECT OF TEST TEMPERATURE ON DRAWN TUNGSTEN WIRE (6, p.9)

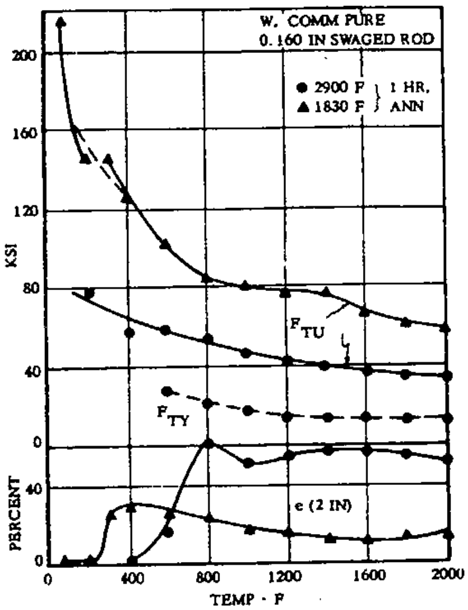

FIG. 3.0313 EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF SWAGED ROD (1, p.5)

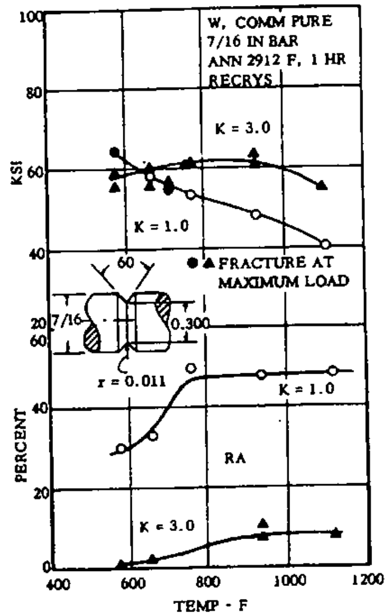

FIG. 3.0331 EFFECT OF TEST TEMPERATURE ON TENSILE STRENGTH OF NOTCHED AND UNNOTCHED RECRYSTALLIZED BAR (3, p.54)

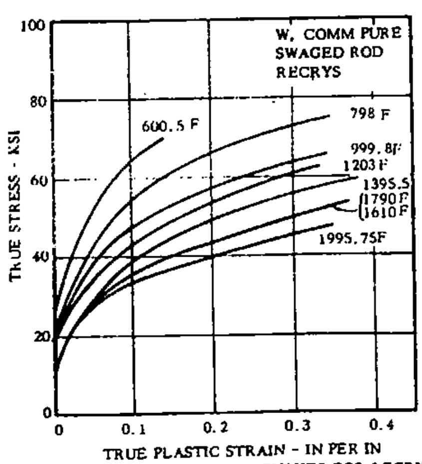

FIG. 3.0314 STRESS STRAIN CURVES FOR RECRYSTALLIZED SWAGED ROD (1, p.3)

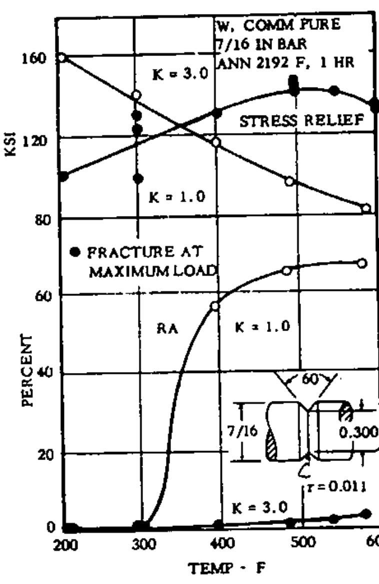

FIG. 3.0332 EFFECT OF TEST TEMPERATURE ON NOTCHED AND UNNOTCHED STRESS RELIEVED BAR (3, p.51)

W, COMM PURE

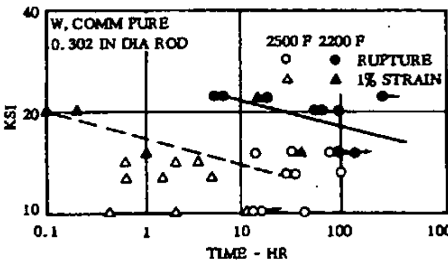

FIG. 3.041 TOTAL STRAIN AND RUPTURE CURVES FOR HIGH PURITY TUNGSTEN AT 2200 F AND 2500 F (4, p.126,128)

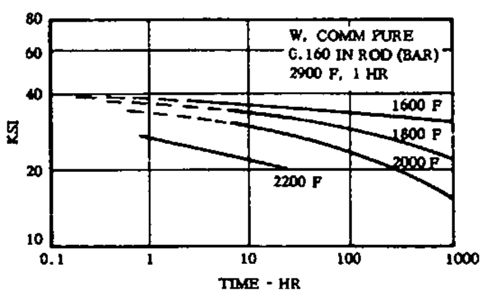

FIG. 3.042 CREEP RUPTURE CURVES FOR RECRYSTALLIZED BAR AT 1600 TO 2200 F (1, p. 8)

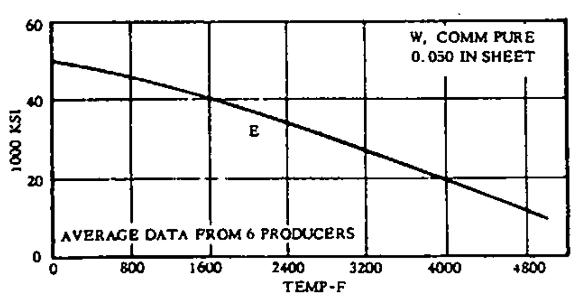

FIG. 3.061 MODULUS OF ELASTICITY AT VARIOUS TEMPERATURES (4, p. 131)

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