DMIC Report 191
September 27, 1963

THE ENGINEERING PROPERTIES OF TUNGSTEN AND TUNGSTEN ALLOYS

DEFENSE METALS INFORMATION CENTER
Battelle Memorial Institute
Columbus 1, Ohio

The Defense Metals Information Center was established at Battelle Memorial Institute at the request of the Office of the Director of Defense Research and Engineering to provide Government contractors and their suppliers technical assistance and information on titanium, beryllium, magnesium, refractory metals, high-strength alloys for high-temperature service, corrosion- and oxidation-resistant coatings, and thermal-protection systems. Its functions, under the direction of the Office of the Secretary of Defense, are as follows:

1. To collect, store, and disseminate technical information on the current status of research and development of the above materials.

2. To supplement established Service activities in providing technical advisory services to producers, melters, and fabricators of the above materials, and to designers and fabricators of military equipment containing these materials.

3. To assist the Government agencies and their contractors in developing technical data required for preparation of specifications for the above materials.

4. On assignment, to conduct surveys, or laboratory research investigations, mainly of a short-range nature, as required, to ascertain causes of troubles encountered by fabricators, or to fill minor gaps in established research programs.

Contract No. AF 33(616)-7747
Project No. 2(8-8975)

DMIC Report 191
September 27, 1963

THE ENGINEERING PROPERTIES OF TUNGSTEN AND TUNGSTEN ALLOYS

by

F. F. Schmidt and H. R. Ogden

to

OFFICE OF THE DIRECTOR OF DEFENSE RESEARCH AND ENGINEERING

DEFENSE METALS INFORMATION CENTER
Battelle Memorial Institute
Columbus 1, Ohio

FOREWORD

The growing interest in the use of columbium, molybdenum, tantalum, and tungsten metals and their alloys for structural applications has emphasized the need for an up-to-date review of some of the more important physical, mechanical, and metallurgical properties of these materials. Four consecutively numbered reports covering columbium and columbium alloys, molybdenum and molybdenum alloys, tantalum and tantalum alloys, and tungsten and tungsten alloys have been prepared. The intent of these reports has been to assemble, present, and summarize, in easy reference form, the present state of the art of these four refractory metals and alloys. This report covers tungsten and tungsten alloys.

In addition to data available from the published literature, numerous organizations have contributed data for inclusion in this report. The Defense Metals Information Center gratefully acknowledges the assistance of the following individuals and organizations who contributed valuable information used in the preparation of this report.

G. D. McArdle and F. Nair, Climax Molybdenum Company
H. Peters, E. I. du Pont de Nemours Company, Inc.
R. L. Wilkey, Fansteel Metallurgical Corporation
R. Bancroft and M. Schussler, Haynes Stellite Company
G. P. Trost, Metals and Controls, Inc.
R. W. Werner, Lawrence Radiation Laboratory
M. Torti, National Research Corporation
W. Bauer, Stauffer Metals Company
R. B. Bargainnier, Sylvania Electric Products, Inc.
C. Mueller and G. A. Liadis, Universal Cyclops Steel Corporation
S. A. Worcester, Wah Chang Corporation
R. L. Ammon, R. T. Begley, and H. G. Sell, Westinghouse Electric Corporation

TABLE OF CONTENTS

THE ENGINEERING PROPERTIES OF TUNGSTEN AND TUNGSTEN ALLOYS

SUMMARY

This report presents the results of a state-of-the-art survey covering tungsten and ten of its alloys. All data are given in tabular and graphical form covering some of the more important physical, mechanical, and metallurgical properties for each material. References are given at the conclusion of each material section.

INTRODUCTION

The requirements for structural materials for service temperatures in excess of those attainable with present materials of construction has provided the stimulus for the development of refractory metals and alloys. Interest has stemmed largely from the high-temperature structural-engineering requirements associated with military hardware. In the development of the refractory metals, columbium, molybdenum, tantalum, and tungsten, and their alloys, extensive studies have been conducted and are in progress which are aimed toward the investigation of fundamental metallurgical concepts, alloy development, pilot scale-up development of promising compositions, and, ultimately, alloy commercialization.

This report reviews some of the more important properties of tungsten and ten of its alloys. Of this group of alloys, several have not reached true commercial status; however the potential of these advanced experimental and pilot-production alloys warrants consideration. All data are presented in tabular and graphical form according to a number of important physical, mechanical, and metallurgical properties for tungsten and each of its ten alloys. Properties and alloys covered in this report are listed in Table 1.

Current tungsten-alloy development work is aimed toward either decreasing the ductile-to-brittle transition temperature or improving the elevated-temperature strength characteristics or both.

In preparing this state-of-the-art survey, technical journals and publications, research reports, and trade literature made available to the Defense Metals Information Center were supplemented with personal contacts with a number of individuals and organizations actively engaged in the refractory-metals field. References are given at the conclusion of each material section.

TABLE 1. ALLOYS AND PROPERTY DATA COVERED IN THIS REPORT

Alloy Composition	Identification of Material	Designation	Chemical Composition	Forms Available	Physical Properties	Melting Point	Density	Thermal Expansion	Thermal Conductivity	Electrical Resistivity	Mechanical Properties	Tensile Properties	Ultimate Tensile Strength	Tensile Yield Strength	Elongation	Reduction in Area	Modulus of Elasticity	Notched Tensile Properties	Creep and Stress-Rupture Properties	Other Selected Mechanical Properties	Metallurgical Properties	Fabricability	Transition Temperature*	Weldability	Stress-Relief Temperature	Recrystallization Temperature
Tungsten		x	x	x		x	x	x	x	x			x	x	x	x	x	x	x	x		x	x	x	x	x
"Doped" Tungsten		x	x	x		x	x			x			x	x	x				x	x		x	x		x	x
W-0.38TaC			x	x		x	x						x	x	x	x			x			x			x	x
W-1ThO$_2$			x	x		x	x						x									x	x		x	x
W-2ThO$_2$			x	x		x	x						x	x	x	x			x			x	x		x	x
W-0.6Cb			x	x		x	x						x	x	x	x			x			x	x		x	x
W-2Mo			x	x		x	x						x	x	x	x						x	x			x
W-15Mo			x	x		x	x						x	x	x	x	x		x			x	x		x	x
W-3Re		x	x	x		x	x			x			x	x	x					x		x	x		x	x
W-5Re			x	x		x	x			x			x	x	x					x		x	x		x	x
W-26Re			x	x		x	x			x			x		x					x		x	x			x

ORGANIZATION OF DATA PRESENTED IN THE APPENDIX

1. Identification of Material

   Designation
   Chemical composition
   Forms available

2. Physical Properties

   Melting point
   Density
   Thermal expansion
   Thermal conductivity
   Electrical resistivity

3. Mechanical Properties

   Tensile Properties at Room Temperature

      Ultimate tensile strength
      Tensile yield strength
      Elongation
      Reduction in area
      Modulus of elasticity

   Effect of Temperature on Tensile Properties

      Ultimate tensile strength
      Tensile yield strength
      Elongation
      Reduction in area
      Modulus of elasticity

   Notched Tensile Properties

   Creep and Stress-Rupture Properties

   Other Selected Mechanical Properties

4. Metallurgical Properties

   Fabricability
   Transition temperature
   Weldability
   Stress-relief temperature
   Recrystallization temperature

References

APPENDIX

TUNGSTEN AND ITS ALLOYS

APPENDIX

TUNGSTEN AND ITS ALLOYS

Unalloyed Tungsten

1. Identification of Material

   a. Designation: many, depending upon individual supplier

   b. Chemical composition: Tables A-1 through A-3

   c. Forms available: ingot, billet, bar, plate, sheet, strip, foil, rod, and wire[6]

TABLE A-1. CHEMICAL REQUIREMENTS FOR SINTERED TUNGSTEN[a](1)

Element	Impurity Content, Maximum, weight per cent
C	0.010
O[b]	0.006
N[b]	0.005
H[b]	0.002
Fe	0.005
Ni	0.008
Mo	0.005
Si	0.003
Al	0.003
W[c]	99.95 (minimum)

(a) For billets, bars, rods, and preforms for forging.
(b) Deviations from these limits alone are not cause for rejection due to analytical limitation.
(c) Determined by difference.

TABLE A-2. PURITY RANGES SPECIFIED FOR TUNGSTEN POWDERS(2)

Element	Impurity Content, weight per cent	
	Sintered Product	Melted Product
C	0.001-0.02	0.005-0.01
O	0.05 -0.5	0.01 -0.03
N	0.001-0.03	0.001-0.003
H	0.005-0.01	--
Al	<0.001-0.01	<0.001-0.002
Cb	--	--
Fe	0.001-0.05	<0.001-0.003
Mo	0.0025-0.05	0.003-0.01
Ni	<0.001-0.03	<0.001-0.002
Si	<0.001-0.05	<0.001-0.002

TABLE A-3. REPRESENTATIVE ANALYSES OF TUNGSTEN AS PRODUCED BY VARIOUS PROCESSES

	Impurity Content, ppm					
				Ingot, Made by		
	Powder-Metal Product			Consumable-Electrode Process		Electron-Beam
Element	Ref. (3)	Ref. (4)	Ref. (5)	Ref. (3)	Ref. (4)	Process(2)
C	4-200	4-47	10-30	26-42	30	20
H	0.2-3	1-3	0.1-1	1	1	<10
N	0.4-80	15-39	6-28	1.8-3	3	10
O	4-131	25-45	5-29	3-20	20	60
Al	8-170	--	<2-40	<5	--	<10
B	--	--	<2	--	--	--
Ca	<5-50	--	<10	<10	--	--
Cr	<5-120	40-120	<5-15	<5	--	<10
Cu	<3-10	--	<1	2-<5	2	<10
Fe	2-340	160-340	10-30	10-40	40	20
K	--	--	<10	--	--	--
Mg	<3-<10	--	--	--	--	--
Mn	--	--	<1	--	--	10
Mo	25-400	180-390	<10-50	50	--	--
Na	--	--	<10-10	--	--	<10
Ni	<10-50	--	2-15	<5-5	5	--
P	--	--	<20	--	--	--
Pb	--	--	<10	--	--	--
S	--	--	<10-10	--	--	--
Si	0-170	30-90	<3-10	<5-26	26	<10
Sn	--	--	<3-<5	--	--	--
Th	--	--	<30	--	--	--
Ti	<20-50	--	--	--	--	--

2. Physical Properties

   a. Melting point: 6170 F[7]

   b. Density: 0.697 lb/in.^{3}[7]

   c. Thermal expansion: Figure A-1

   d. Thermal conductivity: Figure A-2

   e. Electrical resistivity: Table A-4
Figures A-3 and A-4

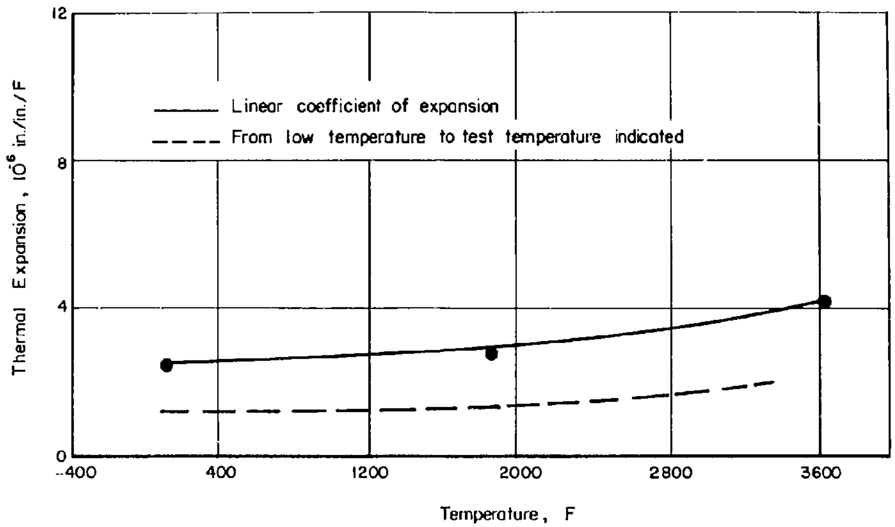


FIGURE A-1. THERMAL EXPANSION OF COMMERCIAL-PURITY TUNGSTEN(8)

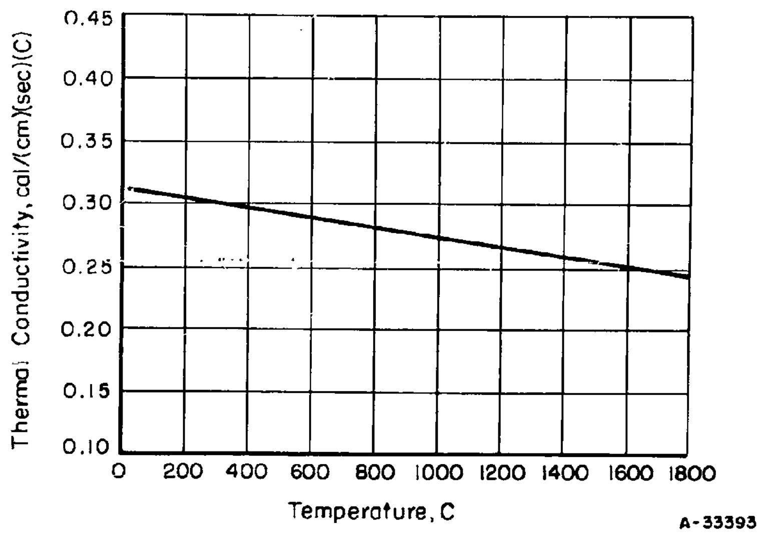


FIGURE A-2. THERMAL CONDUCTIVITY OF COMMERCIAL-PURITY TUNGSTEN(8)

TABLE A-4. EFFECT OF ANNEALING ON SPECIFIC ELECTRICAL RESISTANCE OF DRAWN TUNGSTEN WIRE, ILLUSTRATING THE APPLICABILITY OF MATTHIESEN'S RULE(9)

Annealing Temperature, C	Specific Electrical Resistance (ρ), 10^{-6} ohm-cm	Temperature Coefficient, a	$\rho a \cdot 10^6$, Matthiessen's Rule[a]
--	6.17	0.00355	0.0220
300	6.00	0.00371	0.0222
400	5.91	0.00376	0.0223
550	5.47	0.00405	0.0221
600	5.43	0.00415	0.0225
650	5.30	0.00432	0.0229
700	5.28	0.00432	0.0228
800	5.23	0.00433	0.0227
1000	5.18	0.00440	0.0228
1200	5.00	0.00432	0.0226
2500	4.84	0.00481	0.0232

(a) For annealed tungsten, ρa is about 0.0226×10^{-6}.

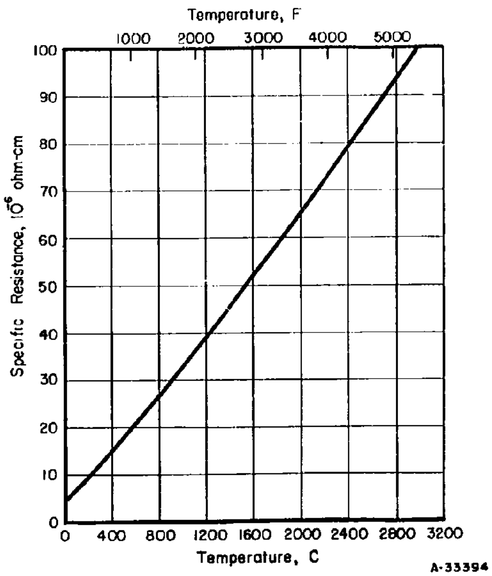
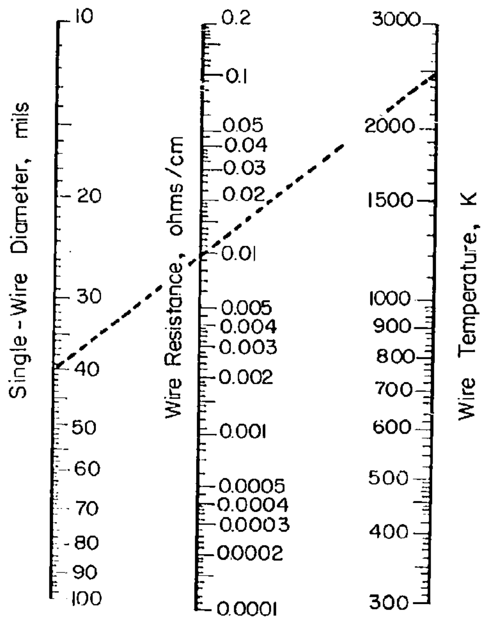
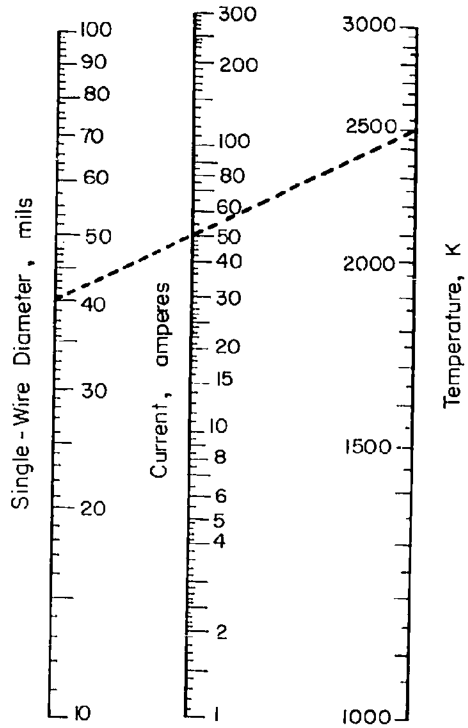


FIGURE A-3. SPECIFIC RESISTANCE OF COMMERCIAL-PURITY TUNGSTEN(8)



Find the resistance per cm length of a 40-mil tungsten wire operating at 2500 K.

Answer: 0.0098



A-45846

Find the current required to obtain 2500 K in a 40-mil tungsten wire.

Answer: 50 amp.

FIGURE A-4. RESISTANCE-TEMPERATURE AND CURRENT-TEMPERATURE NOMOGRAPHS FOR TUNGSTEN WIRE[10]

3. Mechanical Properties

a. Tensile Properties at Room Temperature

Ultimate tensile strength: Tables A-5 and A-10

Tensile yield strength: Tables A-5 and A-10

Elongation: Tables A-5 and A-10

Modulus of elasticity:

Value, 10^6 psi	Reference
47-52	(12)
50	(7)
59	(8)
60	(14)

b. Effect of Temperature on Tensile Properties

Ultimate tensile strength: Tables A-6 through A-11
Figures A-5 through A-9 and A-11a through A-14a

Tensile yield strength: Tables A-6 through A-10
Figures A-6 and A-9 and A-11b through A-14b

Elongation: Tables A-6 through A-11
Figures A-6 and A-10 and A-11c through A-12c

Reduction in area: Tables A-6 through A-9
Figures A-6, A-7, A-10, and A-11d through A-13d

Modulus of elasticity: Table A-7 and Figure A-15

c. Notched Tensile Properties

Figures A-16 through A-18

d. Creep and Stress-Rupture Properties

Tables A-12 through A-15
Figures A-19 through A-21

e. Other Selected Mechanical Properties

Hardness: Figure A-22
Fatigue: Figure A-23

TABLE A-5. SOME SELECTED ROOM-TEMPERATURE TENSILE PROPERTIES OF TUNGSTEN

Condition	Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation, per cent	Reference
Stress-relieved sheet	200 (L)	199 (L)	3 (L)	(11)
(5 min 2060 F, 0.062 inch)[a]	203 (T)	202 (T)	0.1 (T)	(11)
Stress-relieved sheet	185	--	--	(12)
(0.020 inch)[b]	202	--	--	(12)
	236	--	--	(12)
Sheet (0.050 inch)[c]	174	--	0.03	(13)
	233	228	0.53	(13)
	138	--	0.03	(13)
	<73	--	0	(13)
	165	--	0.03	(13)
Sintered ingot	18-20	--	--	(7)
Sintered bar	18	--	--	(8)
Sintered Compact	18.5	--	--	(14)
Swaged bar	50-213	--	--	(8)
Swaged rod	50-150	--	--	(14)
Swaged rod	50-200	--	--	(7)
Wrought wire	285	--	3	(15)
Recrystallized wire	80	--	0	(15)
Drawn wire				
1 mm	286	--	--	(14)
0.2 mm	356	--	--	(14)
0.1 mm	427	--	--	(14)
0.02 mm	570-590	--	--	(14)
Recrystallized wire	157	--	--	(14)
Drawn wire				
0.04 in	256	--	1-4	(8)
0.02 in	284	--	1-4	(8)
0.008 in	355	--	1-4	(8)
0.004 in	427	--	1-4	(8)
0.0008 in	582	--	1-4	(8)
Recrystallized wire				
0.004 in	156	--	--	(8)

(a) Powder metallurgy. Test rate 0.02 inch per minute crosshead speed. Analyses 0.0046% O and 0.0057% N.

(b) Powder metallurgy. Test rate 0.001 inch per inch per second. Analyses 0.0010-0.0020% O, 0.0001% H, and 0.0014-0.0030% N.

(c) Test rate 0.005 inch per inch per minute. Analyses 0.0007-0.0061% O, 0.0001-0.0002% H, 0.0002-0.0020% N, and 0.0011-0.0036% C.

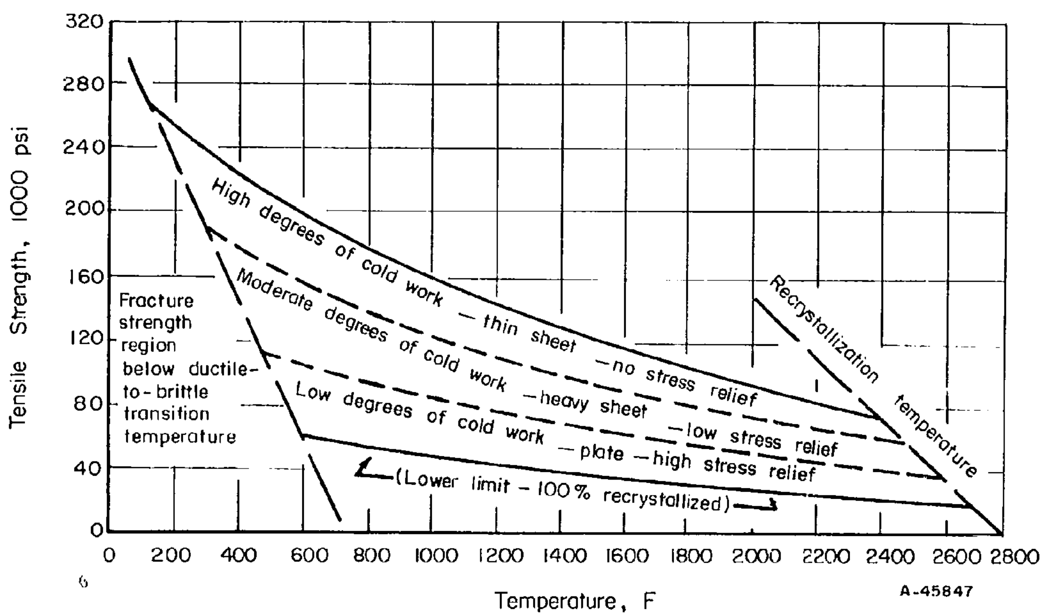


FIGURE A-5. TYPICAL TENSILE-STRENGTH RANGES OF COMMERCIAL-PURITY, POWDER-METALLURGY, TUNGSTEN FLAT-ROLLED PRODUCTS(16)

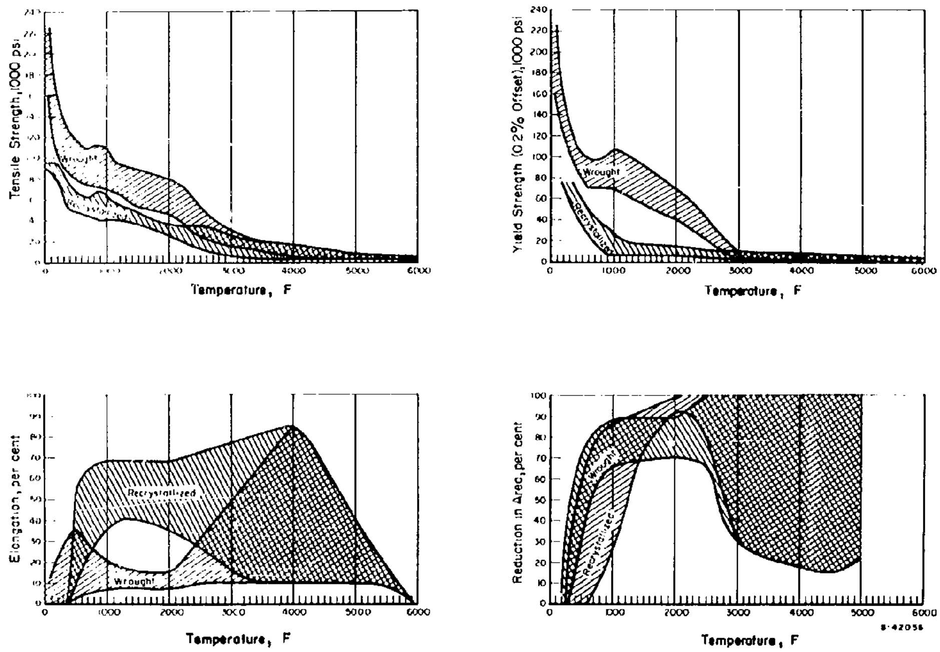


FIGURE A-6. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF TUNGSTEN FROM 0 TO 6000 F[3]

TABLE A-6. DATA FOR MATERIAL TENSILE TESTED AND ILLUSTRATED IN FIGURES A-7 THROUGH A-13

How Consolidated	Specimen Geometry	Metallic Impurity Content, ppm										Interstitial Impurity Content, ppm				Reference
		Al	Ca	Cr	Cu	Fe	Mg	Mo	Ni	Si	Ti	C	H	N	O	
Sintered	Rod	--	--	40	--	210	--	180	--	30	--	4	1	15	25	(17)
Sintered	Rod	--	--	40	--	210	--	180	--	30	--	4	1	15	25	(18)
Sintered	Rod	--	--	70	--	280	--	230	--	90	--	5	--	37	43	(18)
Sintered	Rod	--	--	100	--	260	--	250	--	30	--	47	3	39	35	(18)
Sintered	Rod	--	--	120	--	340	--	350	--	50	--	24	2	38	45	(18)
Sintered	Rod	--	--	50	--	160	--	390	--	30	--	26	2	28	35	(18)
Sintered	Rod	35	--	--	--	25	--	--	10	10	--	76	--	0.6	4	(19)
Sintered	Rod	--	--	<5	--	2	--	150	--	<3	--	49	--	1	6	(20)
Arc melted	Rod	<5	<10	<5	<5	10	--	50	<5	<5	--	26	--	1.8	20	(21)
Sintered	Rod	<50	--	50	10	20	<5	<10	<20	<10	<20	10	0.2	<10	5	(22)
Sintered	Sheet	<10	11	<40	<3	40	<5	30	<10	20	--	10	0.8	--	18	(23)
Sintered	Sheet	<10	<5	--	<5	<10	<3	40	<10	<10	--	<10	0.3	<0.5	4	(24)
Arc melted	Rod	--	--	--	2	40	--	--	5	26	--	30	1	3	20	(25)
Sintered	Rod	--	--	--	--	--	--	--	--	--	--	4	2.5	2	35	(25)
Sintered	Rod	8	<10	--	--	53	<10	--	--	0	--	30	1	23	4	(26)
Sintered	Sheet	--	--	--	--	40	--	400	50	--	50	--	--	--	60	(27)
Sintered	Sheet	30	50	30	--	40	<10	50	20	20	20	16	2	58	36	(28)
Arc melted	Sheet	--	--	--	--	--	--	--	--	--	--	42	--	--	3	(29)
Sintered	Sheet	--	--	--	<10	10	--	25	<10	10	--	26	0.2	0.4	5	(30)
Sintered	Rod	--	--	--	--	--	--	--	--	--	--	100	1	30	131	(31)
Sintered	Rod	--	--	--	--	--	--	--	--	--	--	200	--	80	--	(32)

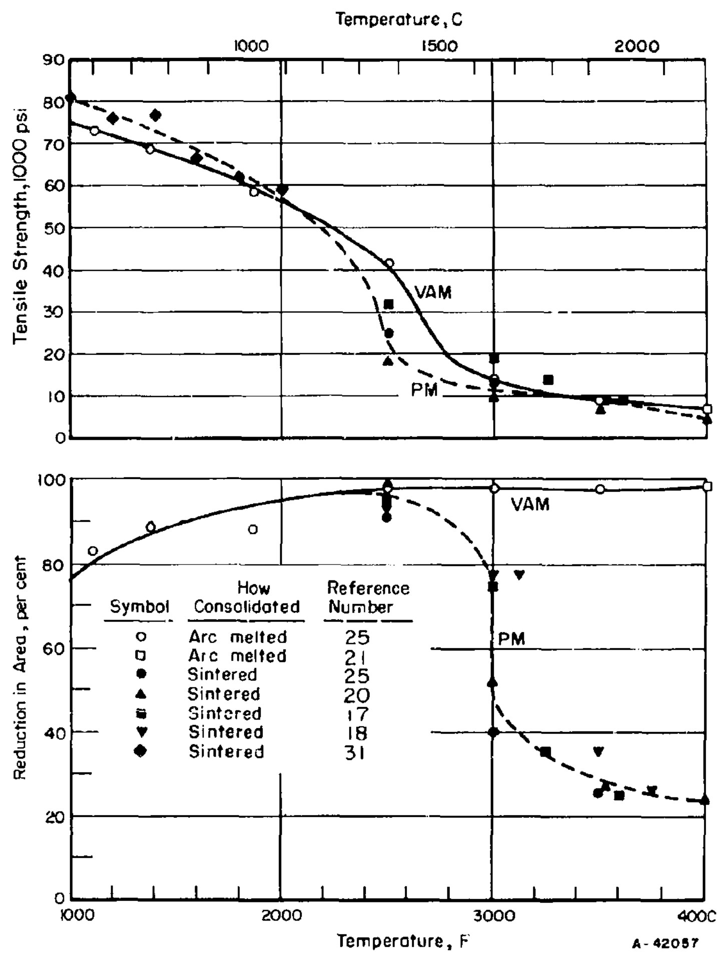


FIGURE A-7. COMPARISON BETWEEN THE CHARACTERISTIC AS-WROUGHT TENSILE PROPERTIES OF VACUUM-ARC-MELTED AND POWDER-METALLURGY TUNGSTEN(3)

Test rate 0.02 inch per inch per minute.

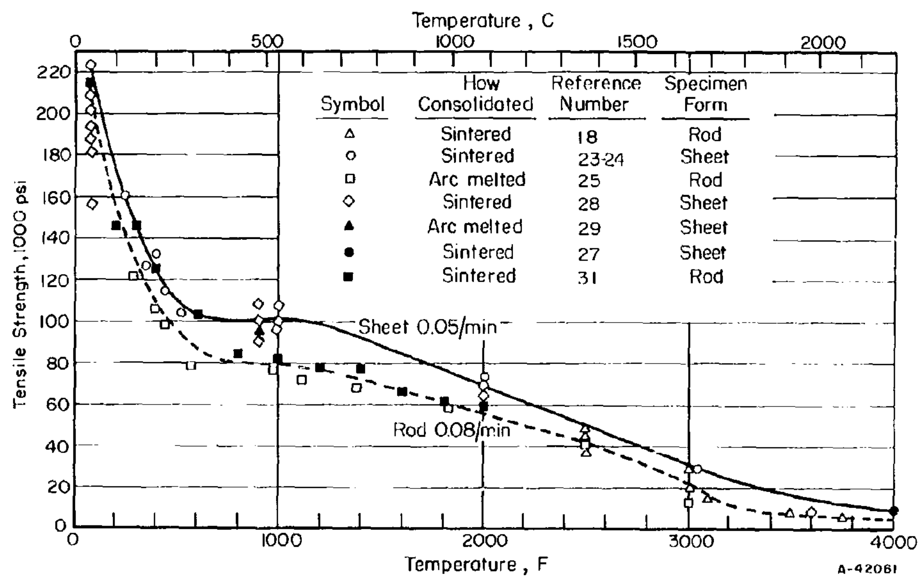


FIGURE A-8. COMPARISON BETWEEN THE TENSILE STRENGTHS OF WROUGHT OR STRESS-RELIEVED TUNGSTEN SHEET AND ROD TESTED AT THE STRAIN RATE INDICATED(3)

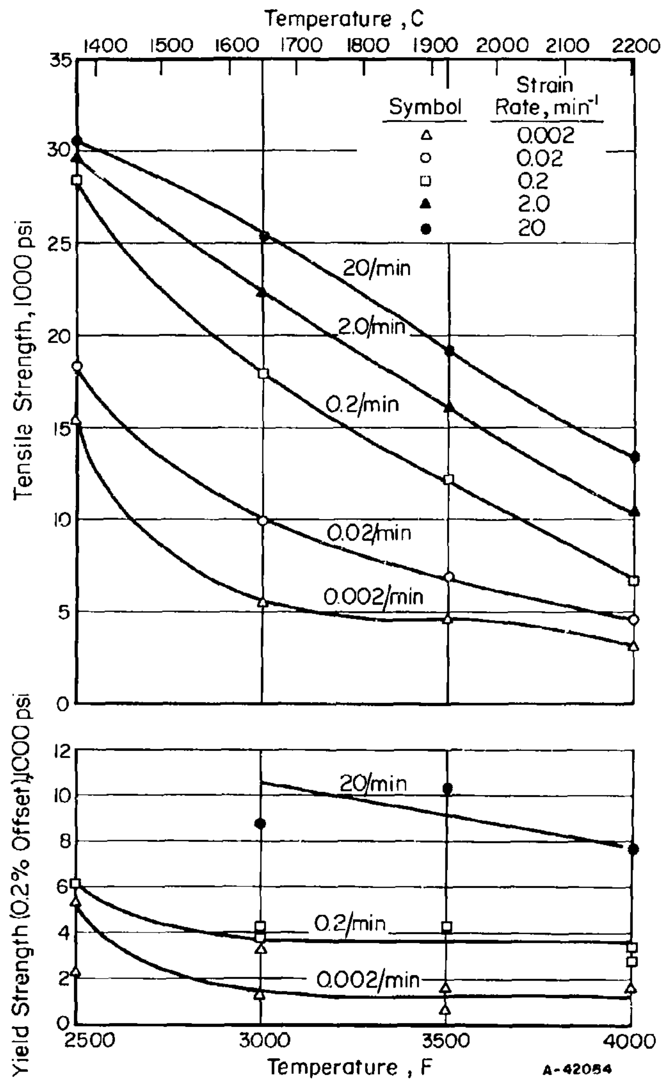


FIGURE A-9. EFFECT OF STRAIN RATE ON THE HIGH-TEMPERATURE PROPERTIES OF RECRYSTALLIZED TUNGSTEN ROD FABRICATED FROM SINTERED BILLETS[20]

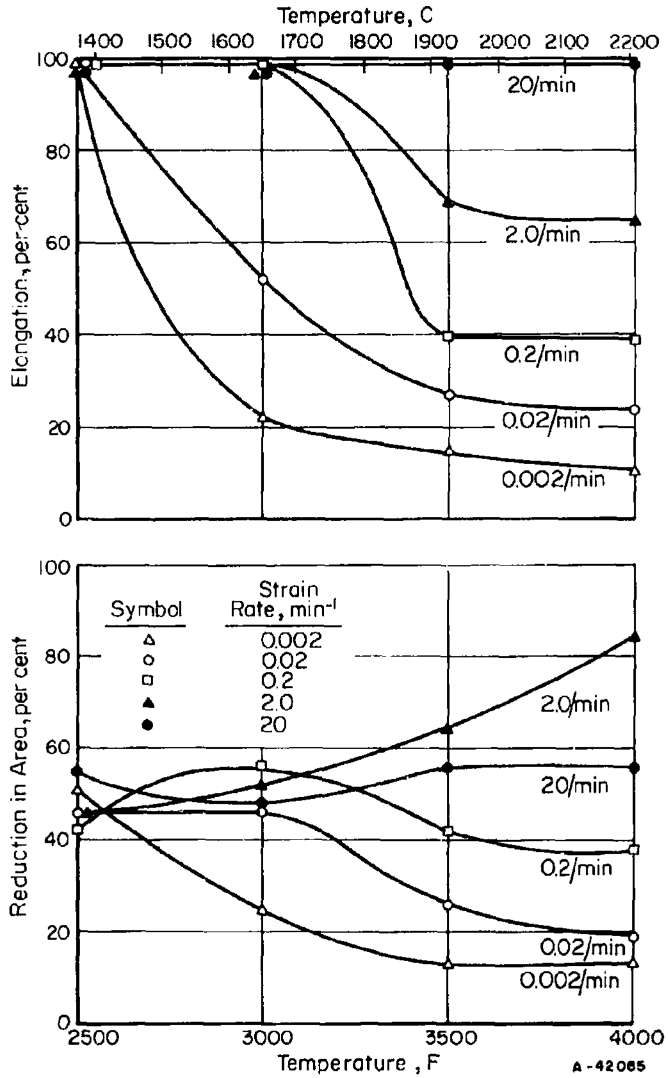
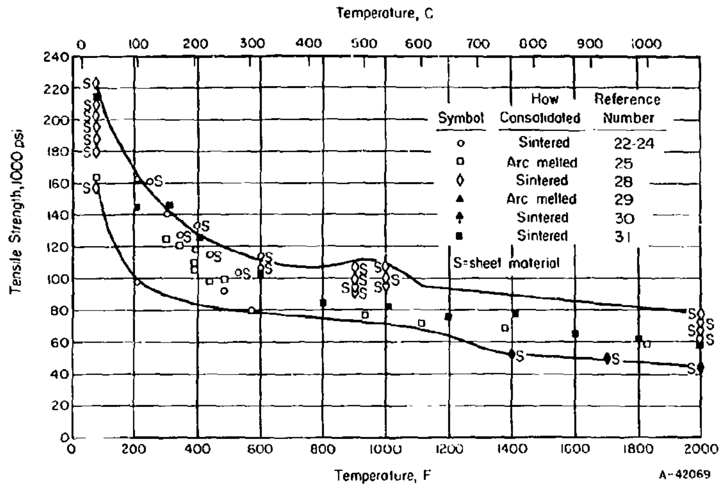


FIGURE A-10. EFFECT OF STRAIN RATE ON THE HIGH-TEMPERATURE DUCTILITIES OF RECRYSTALLIZED TUNGSTEN ROD FABRICATED FROM SINTERED BILLETS[20]



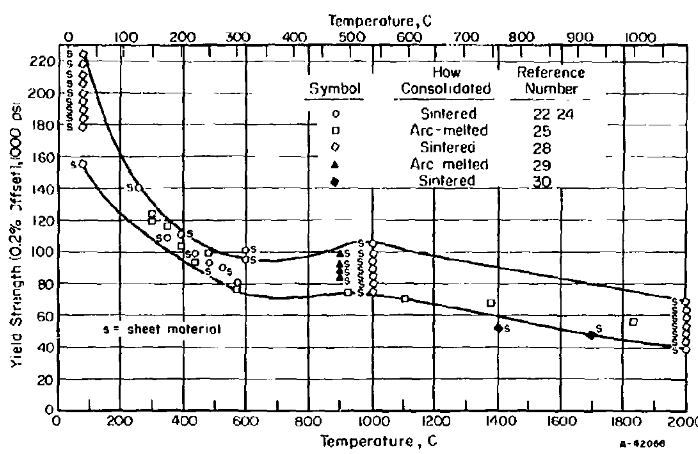
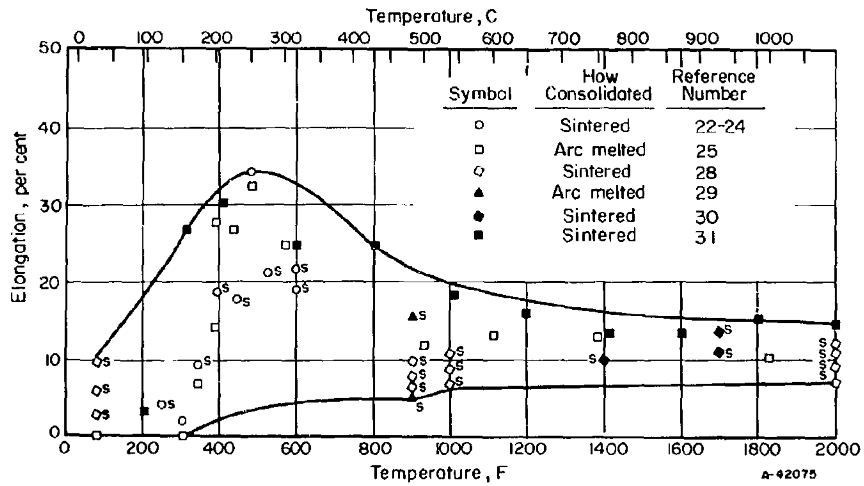


FIGURE A-11. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF WROUGHT OR STRESS-RELIEVED TUNGSTEN FROM 0 TO 2000 F(3)



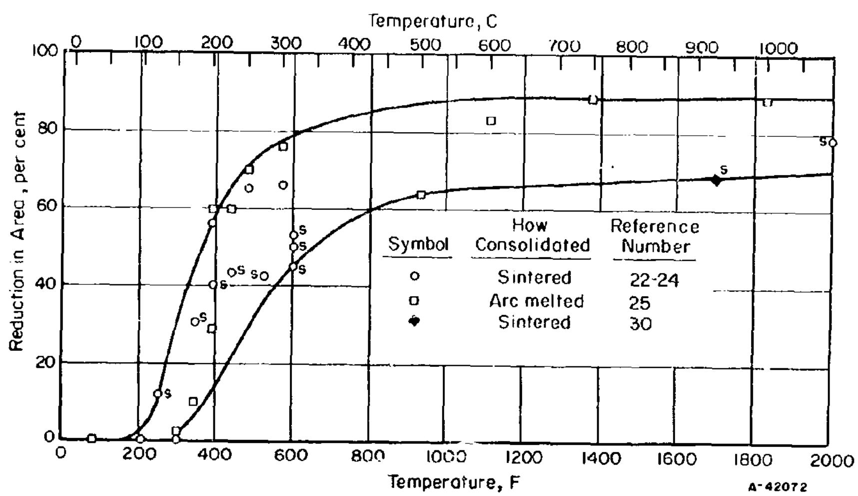
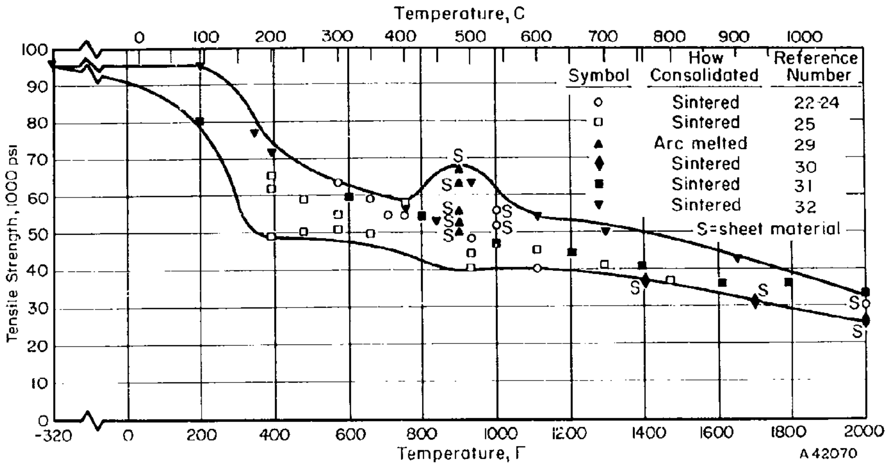


FIGURE A-11. (CONTINUED)



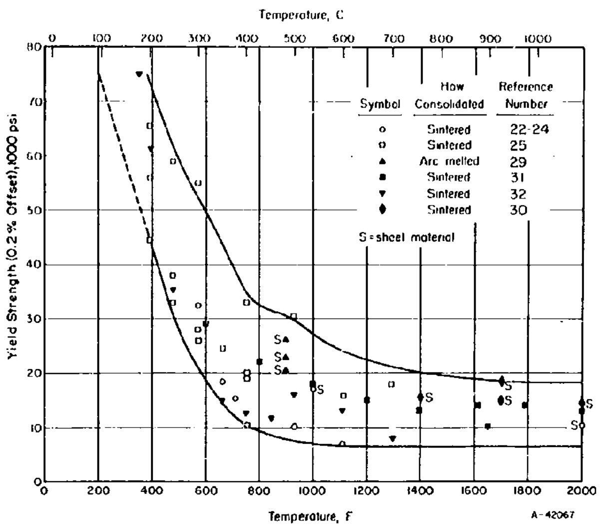
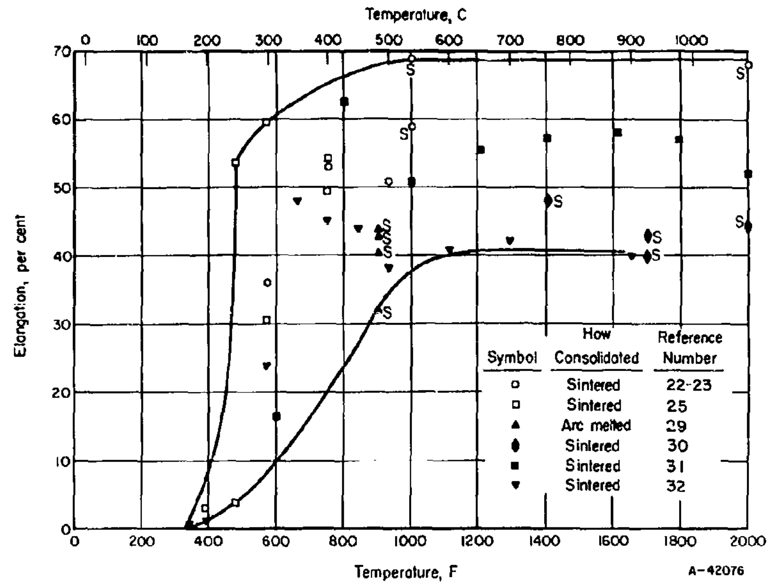


FIGURE A-12. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF RECRYSTALLIZED TUNGSTEN(3)



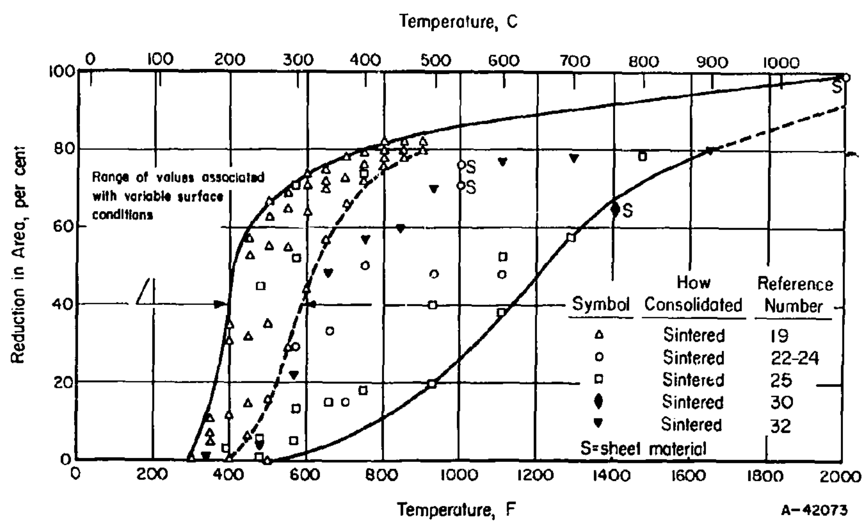
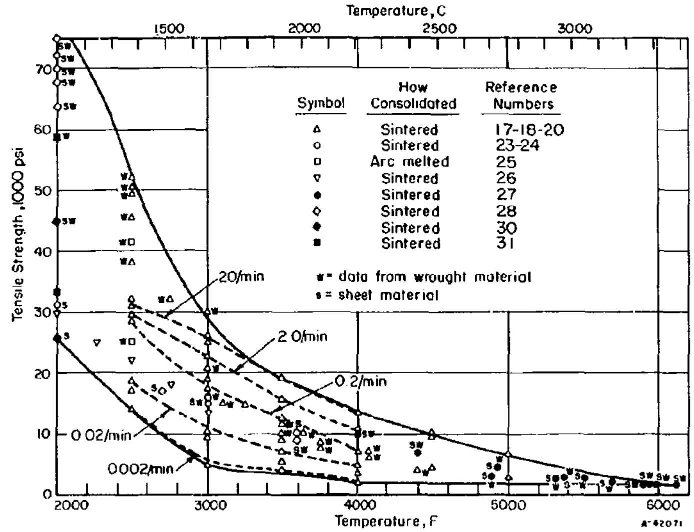


FIGURE A-12. (CONTINUED)



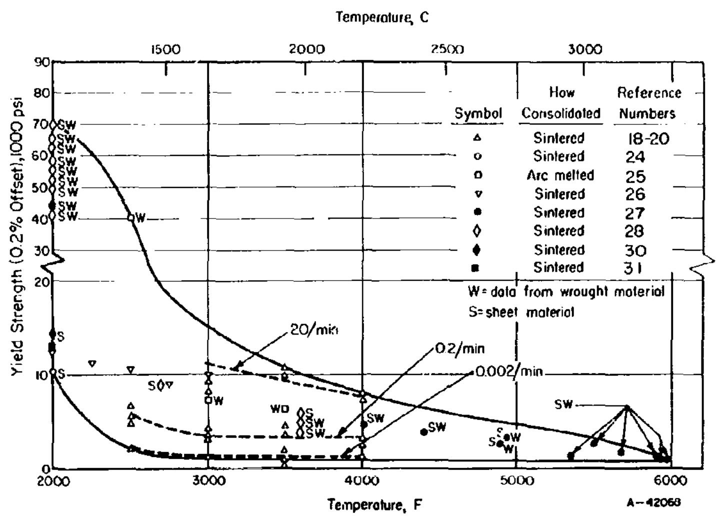
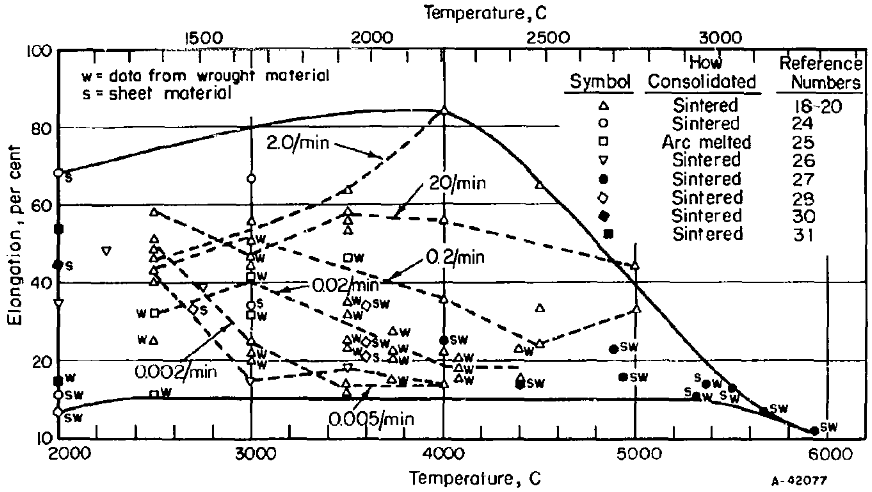


FIGURE A-13. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF TUNGSTEN FROM 2000 TO 6170 F(3)



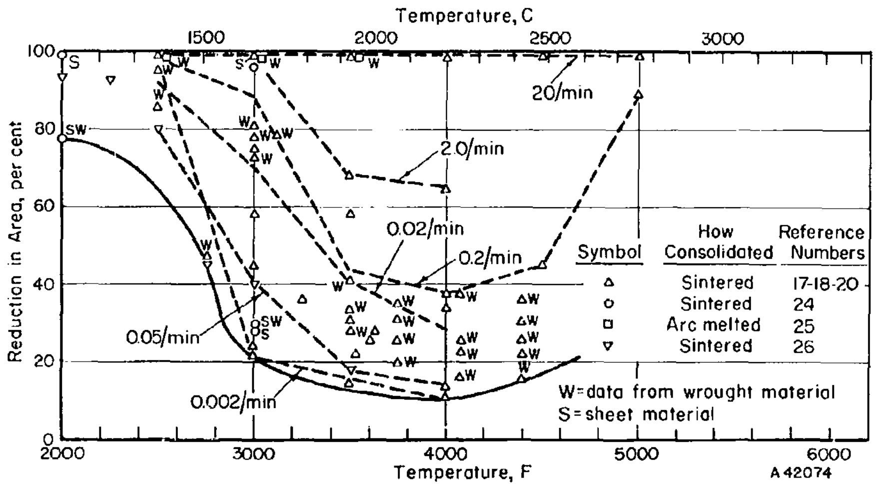


FIGURE A-13. (CONTINUED)

TABLE A-7. TENSILE PROPERTIES OF COMMERCIALLY PURE SINTERED STRESS-RELIEVED TUNGSTEN SHEET[a][12]

Temp, F	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation in 1 Inch, per cent	Modulus of Elasticity, 10^6 psi
		0.020 Inch		
RT	185.0	--	--	49.0
	202.0	--	--	47.0
	236.0	--	--	51.8
1000	146.0	127.0	2.5	37.0
	142.0	124.0	2.5	36.0
1500	135.0	119.0	3.0	34.0
	129.0	115.0	3.0	35.0
2000	105.0	91.0	4.0	31.8
	108.0	93.8	4.5	34.0
2500	53.5	51.9	4.0	28.0
	58.0	56.8	4.5	26.0
2750	23.3	12.0	14.0	--
	23.9	14.8	15.0	--
	38.5	36.7	5.0	--
	31.5	24.8	8.0	--
3000	24.5	16.1	12.5	--
	24.0	12.1	15.0	--
3200	16.8	9.3	18.0	--
	19.3	11.8	14.0	--
3500	13.0	7.1	14.0	9.0
	14.4	8.3	13.0	8.0
4000	11.0	7.8	16.0	--
	10.6	7.0	14.0	--
	11.6	7.6	14.0	--
4500	6.6	4.6	10.0	--
	7.4	4.9	12.0	--
	9.0	6.2	11.0	--
		0.045 Inch		
1500	85.5	72.0	3.5	48.0
2000	78.0	69.2	6.0	41.0
	72.1	62.0	5.5	36.5
2500	49.0	45.7	8.0	29.5
2750	28.7	18.9	11.0	20.0
	34.8	31.0	8.0	24.0
3000	24.0	10.8	16.0	15.0
	21.8	9.8	18.0	16.0
3200	19.4	9.3	13.5	13.3
	18.8	7.6	20.0	15.4

TABLE A-7. (Continued)

Temp, F	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation in 1 Inch, per cent	Modulus of Elasticity, 10^6 psi
		0.045 Inch (Continued)		
3500	15.7	9.2	15.0	--
	14.6	8.5	15.0	7.0
4000	10.8	6.5	13.0	--
	10.9	6.2	14.0	--
4500	5.4	4.2	7.0	--
	7.6	5.2	9.0	--
	6.3	4.2	11.0	--

(a) Test Conditions:

Atmosphere	Argon-7% hydrogen
Analyses	0.0010-0.002% O, 0.0001% H, and 0.0014-0.0030% N
Method of Heating	Resistance
Hold Time of Temperature	5 min
Strain Rate to YS	0.001 in./in./sec
Strain Rate From YS to TS	0.01 in./in./sec

TABLE A-8. ANALYSES OF COMMERCIAL POWDER-METALLURGY TUNGSTEN SHEET FROM FIVE DIFFERENT SOURCES USED TO DETERMINE DATA GIVEN IN TABLE A-9

Element	Impurity Content, ppm				
	Lot				
	A	B	C	D	E
O	5	19	8	13	29
H	0.18	1.03	0.53	0.65	0.13
N	28	17	18	24	6
C	15	20	25	10	30
S	<10	<10	<10	10	<10
Al	<2	<2	<2	<2	40
B	<2	<2	<2	<2	<2
Ca	<10	<10	<10	<10	<10
Cr	<5	<5	<5	<5	15
Cu	<1	<1	<1	<1	<1
Fe	30	20	10	15	10
Mn	<1	<1	<1	<1	<1
Mo	15	10	50	10	<10
Na	10	10	10	10	<10
Ni	7	2	7	15	15
Pb	<10	<10	<10	<10	<10
Si	<3	<3	<3	<3	10
Sn	<5	<5	<5	<5	<3
Th	<30	<30	<30	<30	<30
P	<20	<20	<20	<20	<20
K	<10	<10	<10	<10	<10

TABLE A-9. TENSILE PROPERTIES OF POWDER-METALLURGY TUNGSTEN SHEET[(a)(5)]

Lot	Temperature, F	Tensile Strength, psi	Yield Strength, psi	Elongation, per cent	Reduction in Area, per cent	Average Grain Diameter, cm
A	3880	6950	4570	28.2	14.3	2.7×10^{-3}
0.040	4040	5400	3500	25.0	21.6	--
inch	4150	5430	3530	27.3	29.4	2.5×10^{-3}
	4380	4500	2880	38.2	36.0	--
	4540	3480	2860	--	--	--
	4550	3730	--	37.5	36.2	--
	4670	3950	3300	42.5	47.8	2.9×10^{-3}
	4700	3600	--	48.5	46.2	--
	4900	2240	1910	31.3	99	3.8×10^{-3}
	4980	2060	1980	--	99	--
B	3870	6710	4070	20.6	12.2	--
0.040	4040	5280	3270	42.5	31.0	3.2×10^{-3}
inch	4180	5350	3500	31.3	25.3	--
	4300	4650	3120	29.5	28.9	--
	4410	3650	2890	25.8	30.7	3.1×10^{-3}
	4680	3080	2230	40.6	33.3	4.4×10^{-3}
	4900	2750	2260	38.2	32.7	4.2×10^{-3}
C	3640	7070	3190	62.5	99	3.5×10^{-3}
0.040	3870	6590	3330	62.5	99	3.4×10^{-3}
inch	4030	3770	2260	54.8	99	--
	4250	3120	1670	36.4	99	7.1×10^{-3}
	4410	2520	1250	65.1	99	7.7×10^{-3}
	4670	2150	960	49.2	99	9.5×10^{-3}
	4950	1750	900	54.8	99	1.40×10^{-2}
	5270	1335	675	--	--	--
D	3880	6200	3390	25.0	20.5	3.0×10^{-3}
0.040	4020	5500	3160	28.4	28.5	--
inch	4230	3940	2840	34.3	31.3	3.7×10^{-3}
	4470	3520	2300	40.0	37.1	--
	4700	3000	2580	48.5	39.1	4.1×10^{-3}
	4960	2430	1960	--	41.6	4.2×10^{-3}
	5050	2440	1910	49.3	42.6	--
E	4040	6700	4530	48.5	47	2.3×10^{-3}
0.060	4240	5510	4050	37.5	30.8	2.9×10^{-3}
inch	4440	5080	3860	35	31.7	--
	4700	4340	3490	22	17.4	2.6×10^{-3}
	4940	3620	3220	11	10.8	2.9×10^{-3}

(a) Tested at 0.030 inch per minute crosshead speed.

TABLE A-10. DIRECTIONAL TENSILE PROPERTIES OF POWDER-METALLURGY-PRODUCED TUNGSTEN SHEET[a][11]

Property	Mean	Standard Deviation
Flatness, per cent	5.6[b]	--
Thickness, inch	0.062	0.001
Oxygen Content, ppm	46	28
Nitrogen Content, ppm	57	17
Bend Transition Temperature, F		
Longitudinal	212	28
Transverse	342	36
Longitudinal Tensile Properties		
Room Temperature[c]		
Tensile Strength, 1000 psi	200	26
Yield Strength, 1000 psi	199	26
Elongation, per cent	3	3
1000 F[d]		
Tensile Strength, 1000 psi	99	4
Yield Strength, 1000 psi	91	7
Elongation, per cent	7	1
Transverse Tensile Properties		
Room Temperature[c]		
Tensile Strength, 1000 psi	203	29
Yield Strength, 1000 psi	202	29
Elongation, per cent	0.1	0.3
1000 F[d]		
Tensile Strength, 1000 psi	98	5
Yield Strength, 1000 psi	89	7
Elongation, per cent	7	1
2000 F[e]		
Tensile Strength, 1000 psi	70	4
Yield Strength, 1000 psi	56	7
Elongation, per cent	9	1

(a) Data from 11 sheets fabricated by the following schedule: Sintered billet (1 in. thick) ⟶ longitudinal roll to 0.9 in. at 2640/2550 F ⟶ cross roll to 0.235 in. at 2550/2460 F ⟶ stress relieve 5 min at 2550 F ⟶ longitudinal roll to 0.060 in. at 2280/2010 F ⟶ stress relieve 5 min at 2060 F.

(b) Sheet flatness varied from 1 per cent to 10 per cent.

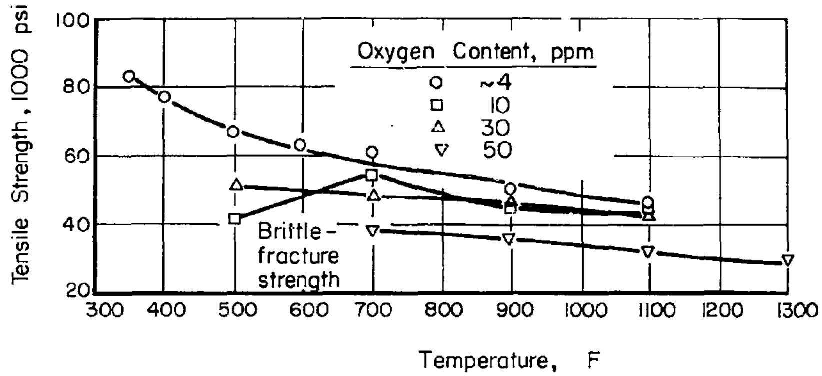
(c) Crosshead speed 0.02 inch per minute.

(d) Tested in air at 0.005 inch per inch per minute to 0.6 per cent offset, and 0.05 inch per inch per minute to fracture.

(e) Strain rate 0.05 inch per inch per minute.

TABLE A-11. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF TUNGSTEN WIRE

Temperature, F	Condition	Diameter, inch	Tensile Strength, 1000 psi	Elongation, per cent	Reference
750	Drawn	0.025	170-227	2-3	8
1470	Drawn	0.025	113-142	4-5	8
2200	Drawn	0.025	57-85	5-6	8
3270	Drawn	0.025	14-42	--	8
70	Drawn	0.028	430	--	7
390	Drawn	0.028	350	--	7
750	Drawn	0.028	320	--	7
1110	Drawn	0.028	240	--	7
1830	Drawn	0.028	100	--	7
3630	Drawn	0.028	20	--	7
5070	Drawn	0.028	5	--	7
68	Drawn	--	285	3	15
1830	Drawn	--	100	6	15
3630	Drawn	--	15	23	15
68	Recrystallized	--	80	0	15
1830	Recrystallized	--	35	10	15
3630	Recrystallized	--	15	23	15



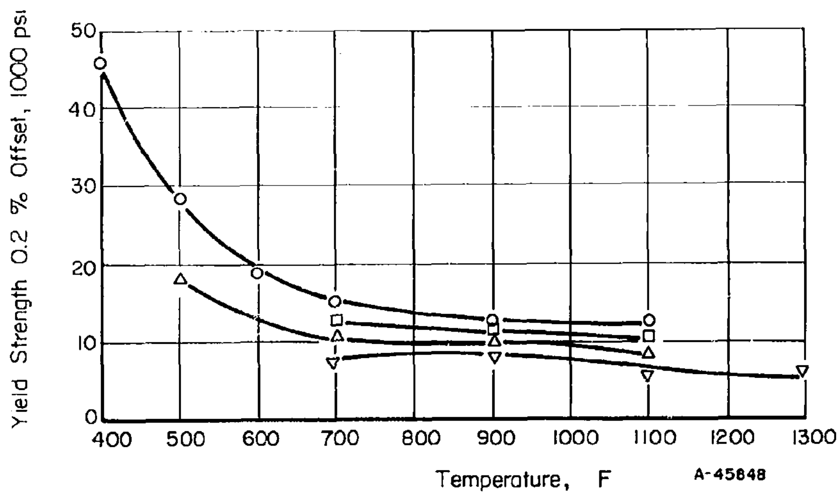


FIGURE A-14. EFFECT OF OXYGEN ON THE TENSILE PROPERTIES OF POWDER METALLURGY TUNGSTEN ROD (0.125 INCH)[33]

Test rate 0.005 inch per minute crosshead.

	Base Material								
Element	C	O	Mo	Fe	K	Al	Si	Cr	Ni
Amount Present, ppm	8	4	20	10	20	10	10	10	10

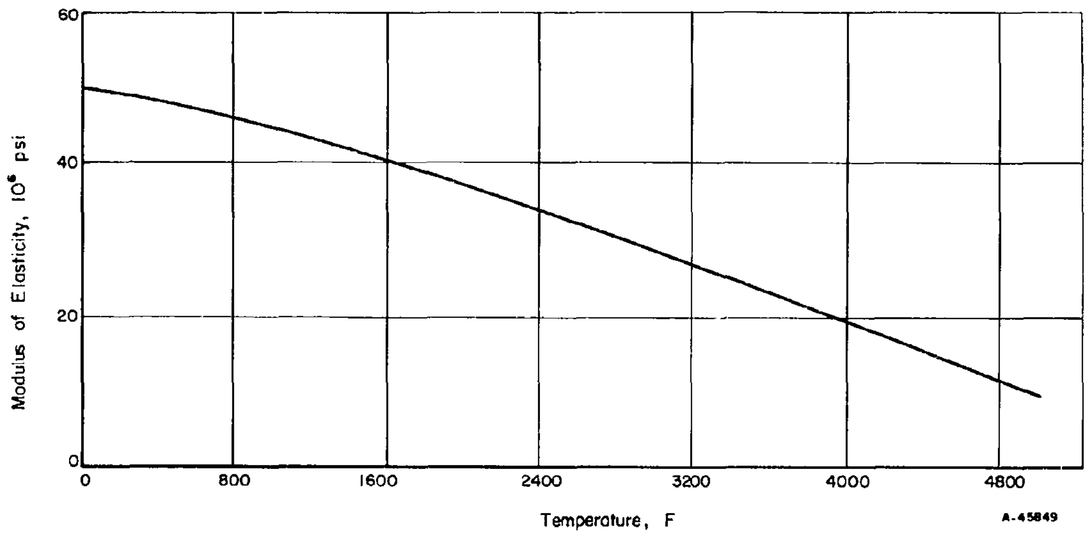


FIGURE A-15. EFFECT OF TEMPERATURE ON THE MODULUS OF ELASTICITY OF OF COMMERCIAL-PURITY TUNGSTEN SHEET (0.050 INCH)(34)

Average data from six producers.

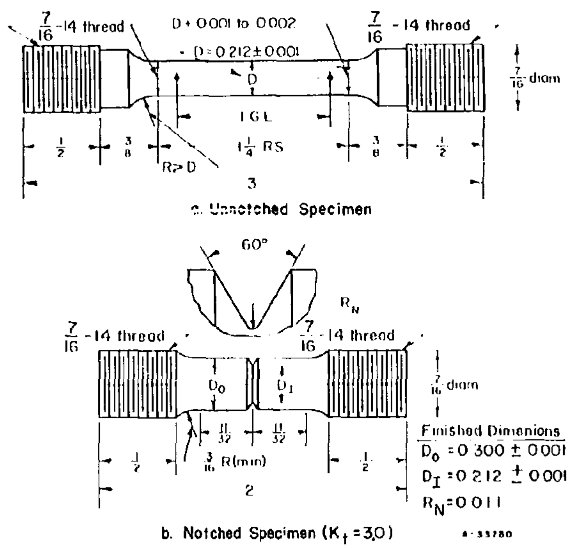


FIGURE A-16. UNNOTCHED AND NOTCHED-BAR TENSILE TEST SPECIMENS USED TO OBTAIN DATA SHOWN IN FIGURES A-17 AND A-18

All dimensions are in inches.

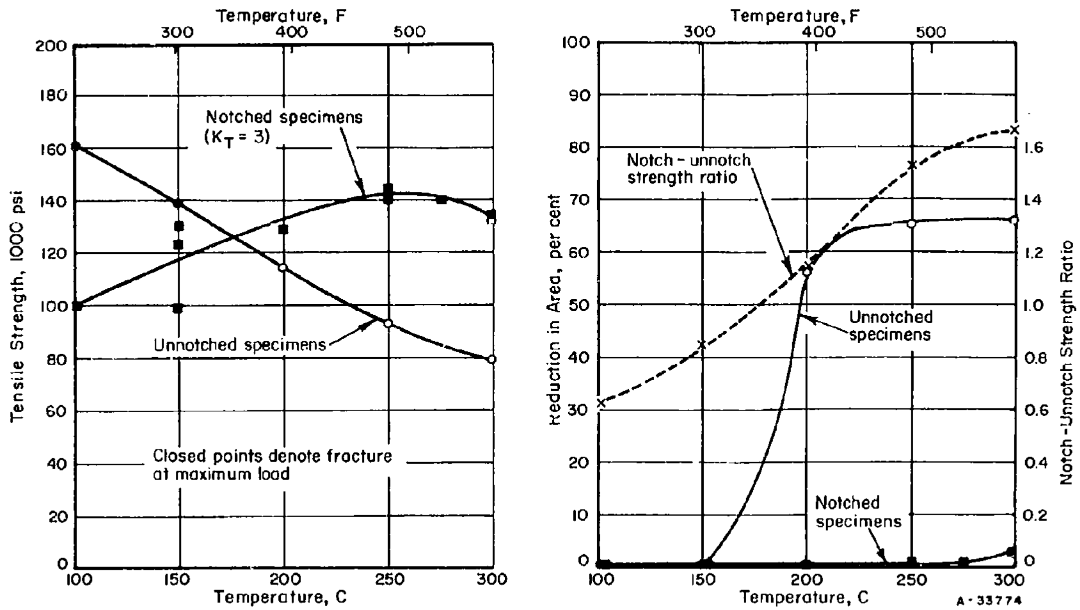


FIGURE A-17. TENSILE PROPERTIES FOR WROUGHT, STRESS-RELIEVED POWDER-METALLURGY TUNGSTEN BAR (1 HR AT 1200 C; HARDNESS, 440 VHN)[22]

	Unnotched	Notched
Crosshead Speed, inch per minute	0.02	0.005

Impurity	Weight Per Cent
C	0.001
O	0.0005
N	<0.001
H	<0.0001

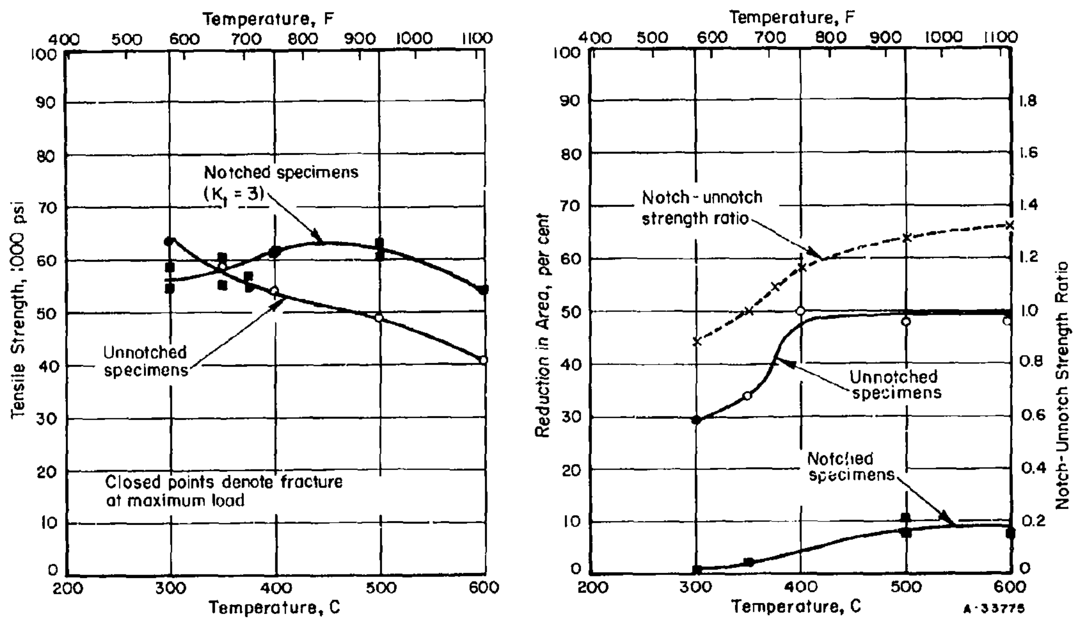


FIGURE A-18. TENSILE PROPERTIES FOR RECRYSTALLIZED POWDER-METALLURGY TUNGSTEN BAR (1 HR AT 1600 C; HARDNESS, 370 VHN; ASTM 4.7)[22]

	Unnotched	Notched
Crosshead Speed, inch per minute	0.02	0.005

Impurity	Weight Per Cent
C	0.001
O	0.0005
N	<0.001
H	<0.0001

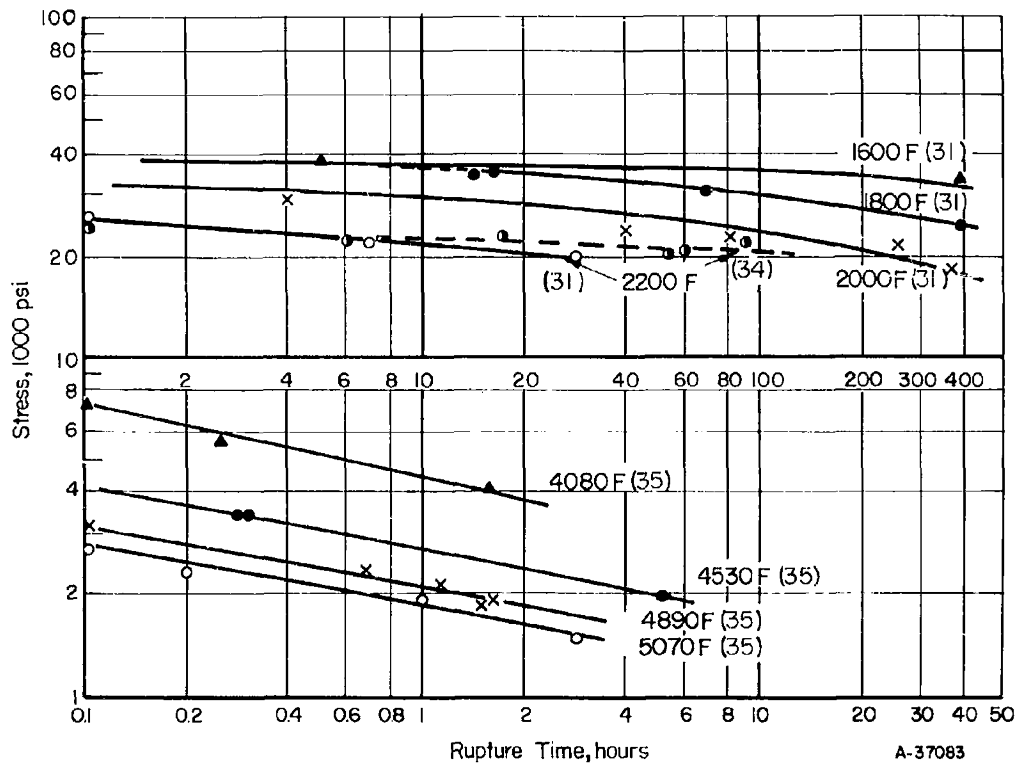


FIGURE A-19. STRESS-RUPTURE PROPERTIES OF TUNGSTEN ROD

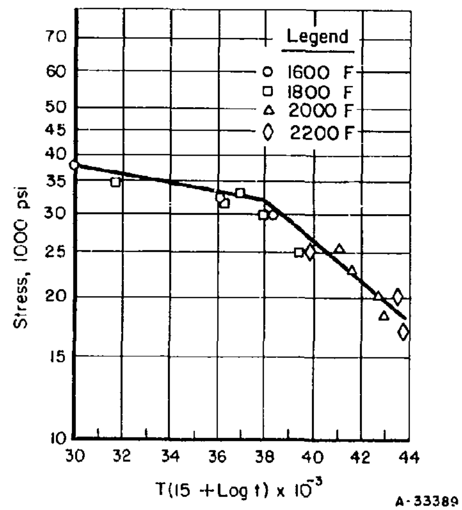


FIGURE A-20. STRESS AS A FUNCTION OF THE LARSON-MILLER PARAMETER FOR RECRYSTALLIZED (1 HOUR 2900 F) TUNGSTEN ROD (0.160 INCH)[31]

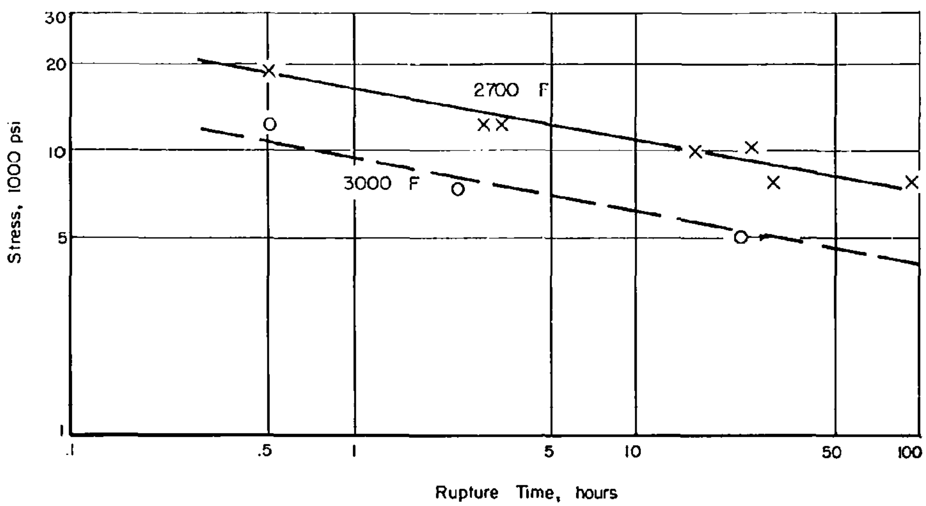


FIGURE A-21. STRESS-RUPTURE DATA FOR COMMERCIALLY PURE TUNGSTEN ROD[26]

TABLE A-12. CREEP AND STRESS-RUPTURE PROPERTIES OF COMMERCIALLY PURE SINTERED STRESS-RELIEVED TUNGSTEN SHEET (0.020 INCH)[a](12)

Temp, F	Stress, 1000 psi	Approx. Thermal Exp., in.	Loading Strain, per cent	Time, sec, to Produce Indicated Plastic Creep 0.05%	0.2%	0.5%	1%	2%	4%	6%	8%	10%	Time to Rupture, seconds	Elong., per cent
2000	100	0.0039	0.3	--	--	--	--	--	--	--	--	--	3.2	3.0
	90	0.0039	0.3	--	--	--	--	--	--	--	--	--	2.0	3.0
	80	0.0039	0.3	5.0	52	163	290	--	--	--	--	--	343	2.0
2500	52	0.0052	0.20	11	37	78	97	102	--	--	--	--	103	3.0
	42	0.0052	0.15	14	70	186	275	310	--	--	--	--	318	3.8
3000	17	0.0075	0.55	4	12	45	140	225	485	670	--	--	695	9.0
	12	0.0075	0.10	7	45	240	501	965	--	--	--	--	--	10.0
	9	0.0075	0.20	45	128	341	1120	--	--	--	--	--	--	17.0
3500	14	0.0075	0.8	--	1.0	3.0	8.5	19	54	75	81	82	84	11
	10	0.0075	0.3	17	70	120	225	385	584	565	581	--	584	9
	10	0.0075	0.3	8	30	81	194	295	505	618	648	--	650	10
	6	0.0075	0.03	252	1560	--	--	--	--	--	--	--	--	11.5
	6	0.0075	0.02	230	1420	--	--	--	--	--	--	--	--	12.0
4000	12	0.0094	1.0	--	0.1	0.8	1.9	3.3	17	33	34	36	37	10.5
	10	0.0094	1.4	--	0.4	1.0	2.1	4.0	11	24	26	27	29	13
	8	0.0094	0.3	5	34	42	122	180	253	262	--	--	265	8
	4	0.0094	--	228	870	--	--	--	--	--	--	--	--	13
4500	7	0.0114	1.6	--	--	0.3	0.9	1.8	3.5	4.2	5.3	6.9	12	14
	6	0.0114	1.3	--	0.2	0.7	2.0	3.1	6.0	8.0	--	--	17	7
	6	0.0114	0.9	0.2	0.8	2.0	4.1	16	25	28	--	--	34	7
	5	0.0114	1.0	--	2.0	4.0	8.3	17	29	43	5.7	72	98	12
	4	0.0114	0.2	7	15	57	82	220	260	301	395	431	436	12

(a) Test Conditions:

Atmosphere	Argon-7% hydrogen
Gage Length	1.0 in.
Sheet Thickness	0.020 in.
Analyses	0.001-0.0020% O, 0.0001% H, and 0.0014-0.003% N
Method of Heating	Resistance

TABLE A-13. CREEP AND STRESS-RUPTURE PROPERTIES OF COMMERCIALLY PURE SINTERED STRESS-RELIEVED TUNGSTEN SHEET (0.045 INCH)(a)(12)

Stress, 1000 psi	Approx. Thermal Exp., in.	Loading Strain, per cent	Time, sec, to produce Indicated Plastic Creep 0.05%	0.2%	0.5%	1%	2%	4%	6%	8%	10%	Time to Rupture, seconds	Elong., per cent
						At 2000 F							
57	0.00024	0.14	1.1	20	241	680	840	844	--	--	--	845	5.0
50	0.00024	0.12	6.8	225	--	--	--	--	--	--	--	--	6.0
40	0.00024	0.10	25	--	--	--	--	--	--	--	--	--	5.0
						At 2500 F							
45	0.0032	0.15	7	54	131	160	178	--	--	--	--	180	6.0
41	0.0032	0.25	--	--	--	--	--	--	--	--	--	2	9.0
41	0.0032	0.20	3.5	23	39	57	64	--	--	--	--	76	5.5
37	0.0032	0.20	--	--	--	--	--	--	--	--	--	2	6.0
34	0.0032	0.10	0.3	1.2	5.0	8.6	10	--	--	--	--	14	7.5
						At 3000 F							
13	0.0075	0.7	1.5	10	45	80	175	410	662	--	--	--	20
11	0.0075	0.6	10	56	72	140	318	685	961	--	--	--	20
9	0.0075	0.2	14	100	335	810	1537	--	--	--	--	--	20
6	0.0075	0.18	22	205	544	1435	--	--	--	--	--	--	20
						At 3500 F							
13	0.008	1.3	--	0.5	1.0	1.8	4.2	13	26	31	--	35	12
11	0.008	0.5	0.2	0.6	1.2	10	40	110	150	155	--	158	9.5
9	0.008	0.2	14	80	180	390	560	842	938	943	--	946	9
9	0.008	0.5	1.1	25	91	227	320	330	--	--	--	347	8
7	0.008	0.1	42	105	345	720	1105	1560	--	--	--	1590	6
5	0.008	--	330	--	--	--	--	--	--	--	--	--	13.5
						At 4000 F							
11	0.0095	1.4	--	--	0.2	0.8	2.4	5.0	8.6	11	12	14	16
11	0.0095	1.7	--	--	--	0.2	1.5	2.5	4.0	5	6	8	15
9	0.0095	0.8	0.1	0.9	1.7	3.2	7.0	17	22	23	24	25	13
7	0.0095	0.4	0.4	5.0	17	45	67	78	81	--	--	83	8
7	0.0095	0.3	0.3	4.0	18	38	70	100	104	106	--	107	10
5	0.0095	0.07	20	107	270	695	1056	--	--	--	--	1250	--
3	0.0095	--	705	--	--	--	--	--	--	--	--	--	14
						At 4500 F							
7	0.012	2.4	--	0.2	0.7	1.3	4.0	6.0	7.5	10	11	13	15
6	0.012	0.8	1.4	6.3	9.0	15	25	46	57	--	--	62	8
6	0.012	0.8	1.1	3.0	5.0	12	20	37	52	68	--	92	9.5
5	0.012	0.2	5.0	35	70	142	180	187	195	--	--	197	8
5	0.012	1.0	2.0	10	24	35	51	63	69	70	--	72	10
5	0.012	1.0	1.7	3.0	7.5	18	36	52	65	68	70	77	12.5
4	0.012	0.14	42	120	195	335	482	540	550	--	--	556	7.5
3	0.012	0.04	103	336	852	--	--	--	--	--	--	--	13

(a) Test Conditions:

Atmosphere	Argon-7% hydrogen
Gage Length	1.0 in.
Sheet Thickness	0.045 in.
Analyses	0.0010-0.0020% O, 0.001% H, and 0.0014-0.003% N
Method of Heating	Resistance

TABLE A-14. STRESS-RUPTURE PROPERTIES OF POWDER-METALLURGY TUNGSTEN SHEET AT 4800 F[(5)]

Lot	Stress, psi	Minimum Creep Rate, sec^{-1}	Rupture Life, min		Average Grain Diameter, cm
A	1500	5.56×10^{-6}	319.3		2.9×10^{-3}
0.040	1800	5.75×10^{-6}	240.4		2.8×10^{-3}
inch	2500	4.09×10^{-5}	39.2		3.2×10^{-3}
				Avg	3.0×10^{-3}
B	1740	8.34×10^{-6}	155.7		3.7×10^{-3}
0.040	1940	3.17×10^{-5}	70.1		4.5×10^{-3}
inch	2470	7.59×10^{-5}	22.9		4.5×10^{-3}
				Avg	4.3×10^{-3}
C	720	3.33×10^{-6}	512		1.5×10^{-2}
0.040	960	1.32×10^{-5}	208.8		1.4×10^{-2}
inch	1460	1.72×10^{-4}	13.2		1.2×10^{-2}
				Avg	1.4×10^{-2}
D	1020	5.33×10^{-6}	>300		--
0.040	1550	1.17×10^{-5}	121.0		4.3×10^{-3}
inch	1800	2.97×10^{-5}	53.9		4.5×10^{-3}
	2500	3.08×10^{-4}	4.6		3.6×10^{-3}
	3000	1.02×10^{-3}	2.8		4.7×10^{-3}
				Avg	4.3×10^{-3}
E	250	4.16×10^{-7}	>1000		--
0.060	670	1.42×10^{-6}	<460		--
inch	1000	1.02×10^{-5}	91.8		3.3×10^{-3}
	1810	--	5.9		--
	1815	2.93×10^{-5}	7.5		3.5×10^{-3}
				Avg	3.4×10^{-3}

(a) Analyses:

Lot	Impurity, ppm O	H	N	C
A	5	<1	28	15
B	19	1	17	20
C	8	<1	18	25
D	13	<1	24	10
E	29	<1	6	30

TABLE A-15. STRESS-RUPTURE PROPERTIES OF DRAWN SINTERED TUNGSTEN WIRE (0.070 INCH)[36]

Temperature, F	Stress, 1000 psi	Time to Rupture, min	Elongation in 2 In., per cent
3000	19.0	54.4	3.5
	17.9	67.3	2.5
	15.5	82.6	1.3
3750	10.0	4.0	1.0
	7.8	24.5	1.3
4000	10.0	0.9	1.0
	7.0	2.7	1.4
	5.0	11.0	0.4
4400	7.0	3.1	1.7
	3.9	43.2	1.7
	2.0	201.0	3.0

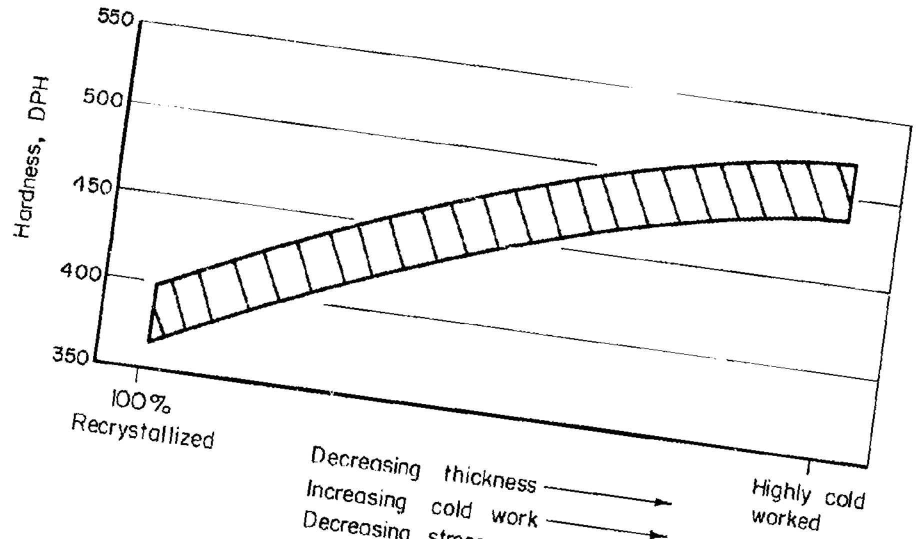


FIGURE A-22. INFLUENCE OF PROCESSING PARAMETERS ON THE HARDNESS OF POWDER-METALLURGY TUNGSTEN FLAT-ROLLED PRODUCTS(16)

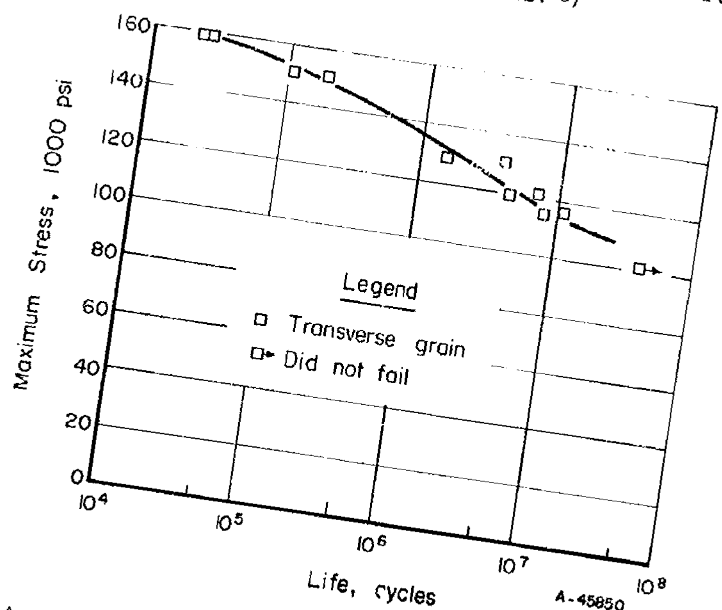


FIGURE A-23. COMPLETELY REVERSED SHEET-BENDING FATIGUE PROPERTIES OF ROLLED TUNGSTEN SHEET (0.020 INCH) AT ROOM TEMPERATURE(37)

4. Metallurgical Properties

   a. Fabricability: initial forging, rolling, or swaging of sintered compacts is done at 2900 to 3300 F; further working is done at successively lower temperatures as reduction in cross section proceeds[7]

   b. Transition temperature: Table A-16 and Figures A-24 through A-34

   c. Weldability: 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; high melting point metals which do not form brittle intermediate phases with tungsten have been successfully spotwelded to tungsten[40]

   d. Stress-relief temperature: 1 hour at 1800 to 2190 F[11, 22]

   e. Recrystallization temperature: Table A-17 and Figure A-35

TABLE A-16. BEND-TRANSITION-TEMPERATURE TESTS FOR COMMERCIALLY PURE SINTERED STRESS-RELIEVED TUNGSTEN SHEET[a][12]

Bend Radius	Temperature, F	Bend Angle, degrees	Remarks
1T	300	35	Fractured
1T	300	40	Fractured
1T	400	41	Fractured
1T	400	90	Fractured
1T	400	95	Fractured
1T	425	91	Fractured
1T	425	150	Fractured
1T	450	105	Fractured
1T	450	126	Fractured
1T	500	129	Fractured
1T	500	120	Fractured
1T	540	120	Fractured
2T	200	0	Fractured
2T	200	0	Fractured
2T	300	55	Fractured
2T	400	80	Fractured
2T	400	103	Fractured
2T	425	180	OK
2T	425	110	Fractured
2T	450	180	OK
2T	450	180	OK
2T	500	180	OK
2T	540	132	Fractured
2T	540	180	OK

(a) Test Conditions:

Heating	Oil bath	Specimens	Transverse to rolling direction
Bend Rate	1.0 in./min		
Sheet Thickness	0.030 in.	Analyses	0.0010-0.0020% O, 0.0001% H, and 0.0014-0.0030% N

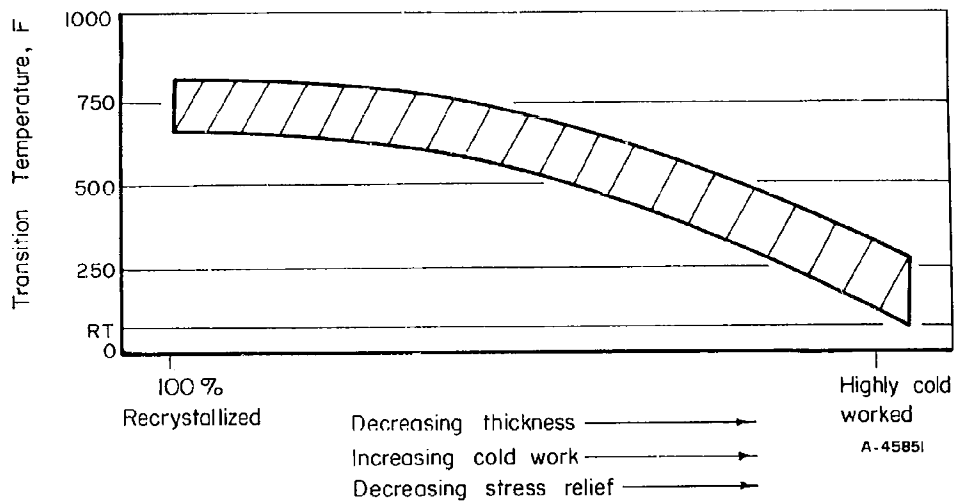


FIGURE A-24. INFLUENCE OF PROCESSING PARAMETERS ON THE DUCTILE-BRITTLE TRANSITION TEMPERATURE OF FLAT-ROLLED POWDER-METALLURGY TUNGSTEN PRODUCTS(16)

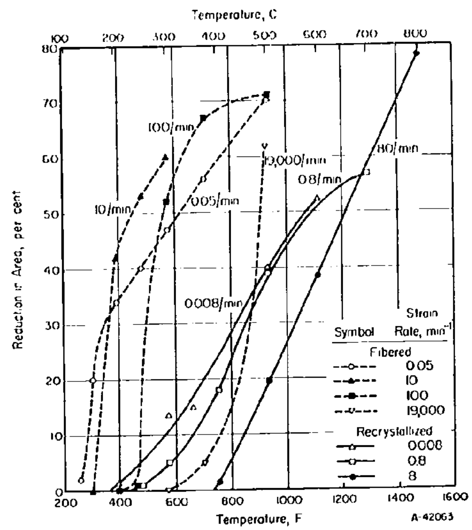


FIGURE A-25. EFFECT OF STRAIN RATE ON THE LOW-TEMPERATURE DUCTILITIES OF FIBERED(38) AND OF RECRYSTALLIZED(25) TUNGSTEN ROD(3)

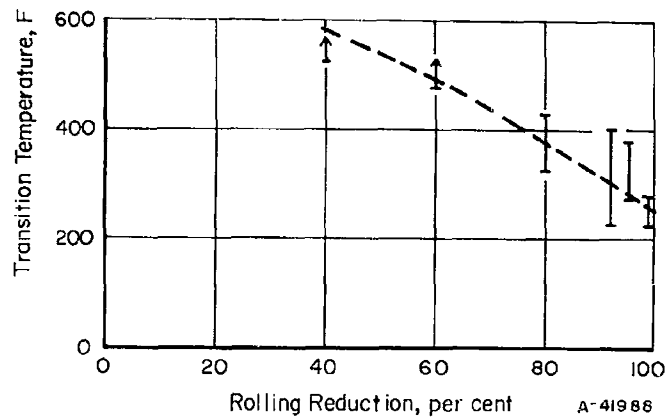


FIGURE A-26. EFFECT OF AMOUNT OF REDUCTION AFTER RECRYSTALLIZATION ON THE BEND-TRANSITION TEMPERATURE OF ARC-MELTED TUNGSTEN SHEET (0.040 INCH)[11]

Stress relieved 1 hour at 1800 F.

Analyses 0.0010% C, 0.0008% O, and 0.0004% N.

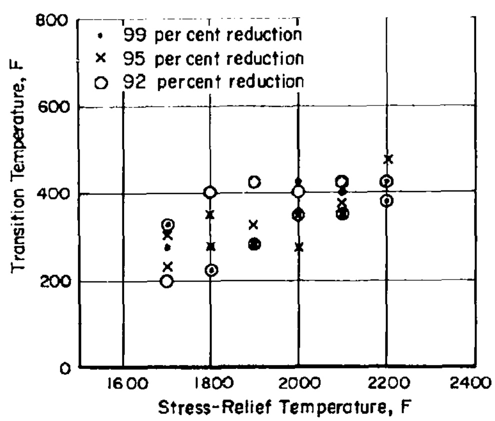


FIGURE A-27. EFFECT OF STRESS-RELIEVING TEMPERATURE (1 HOUR) ON THE BEND-TRANSITION TEMPERATURE OF ARC-MELTED TUNGSTEN SHEET[11]

Maximum and minimum points shown for each stress-relief treatment.

Analyses 0.0010% C, 0.0008% O, and 0.0004% N.

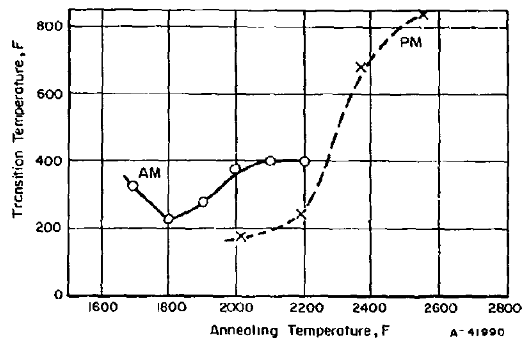


FIGURE A-28. COMPARISON OF BEND-TRANSITION TEMPERATURE OF ARC-MELTED AND POWDER-METALLURGY TUNGSTEN SHEET(11)

How Consolidated	Thickness, inch	Impurity Content, ppm C	O	N
AM	0.040	10	8	4
PM	0.060	--	46	57

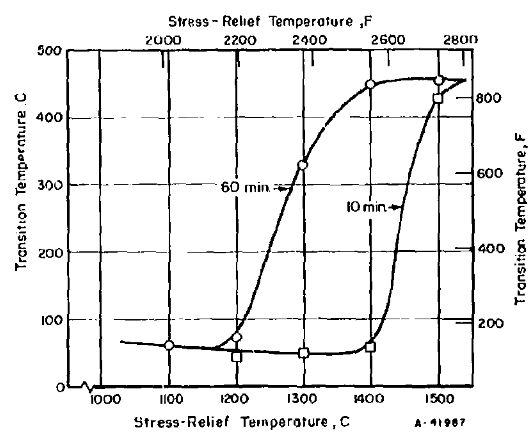


FIGURE A-29. EFFECT OF STRESS-RELIEF TREATMENT ON THE BEND-TRANSITION TEMPERATURE OF WROUGHT POWDER-METALLURGY TUNGSTEN SHEET (0.060 INCH)(11)

Analyses 0.0046% O and 0.0057% N.

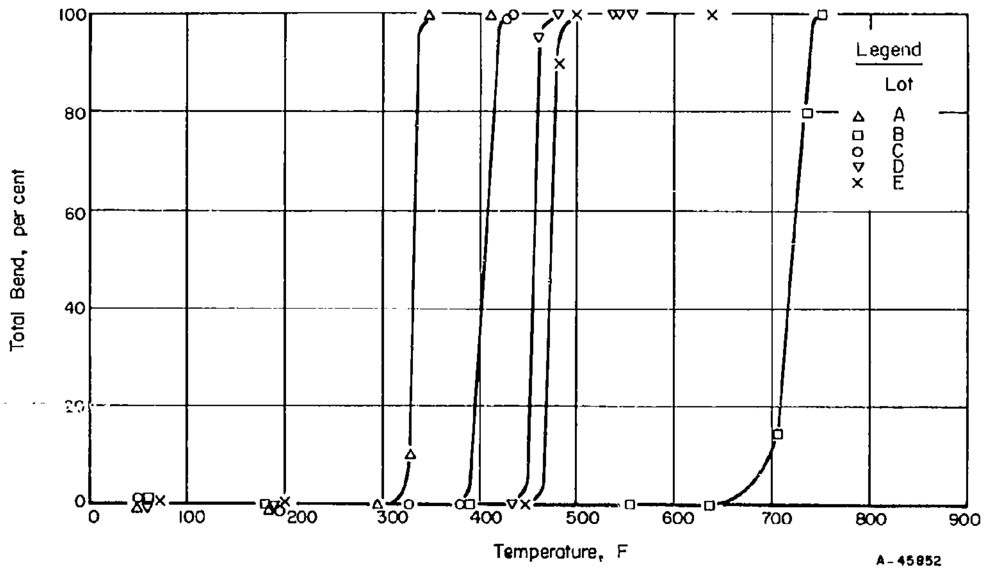


FIGURE A-30. BEND-TRANSITION TEMPERATURE FOR FIVE LOTS OF POWDER-METALLURGY TUNGSTEN SHEET(5)

Loading rate, 4 inches per minute; radius, 0.160 inch

Analyses:

Lot	Sheet Thickness, inch	Impurity Content, ppm			
		O	H	N	C
A	0.040	5	<1	28	15
B	0.040	19	1	17	20
C	0.040	8	<1	18	25
D	0.040	13	<1	24	10
E	0.060	29	<1	6	30

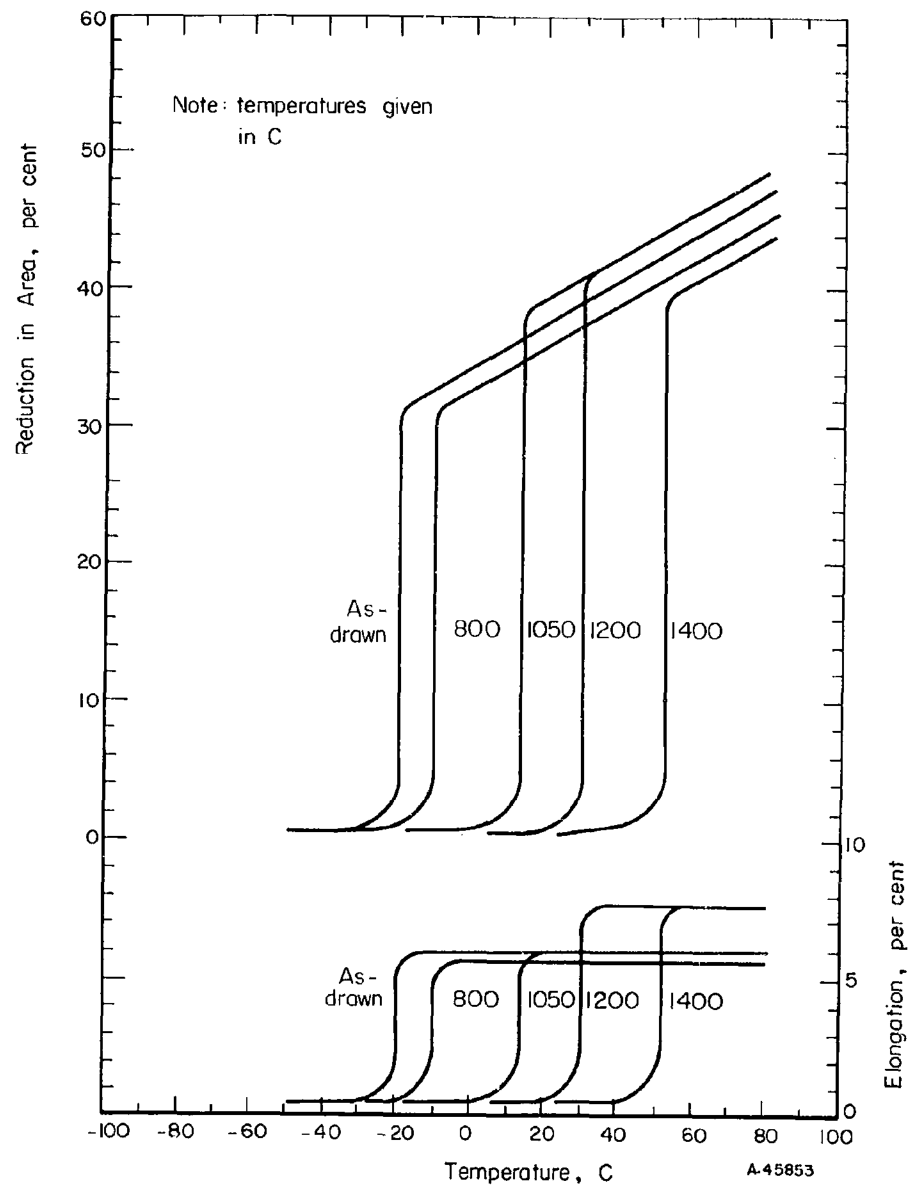


FIGURE A-31. EFFECT OF RECOVERY-ANNEALING (10 MINUTE TIME) ON THE DUCTILE-BRITTLE TRANSITION BEHAVIOR OF TUNGSTEN WIRE (0.030 INCH)(39)

Strain rate 2.8×10^{-4} per second.

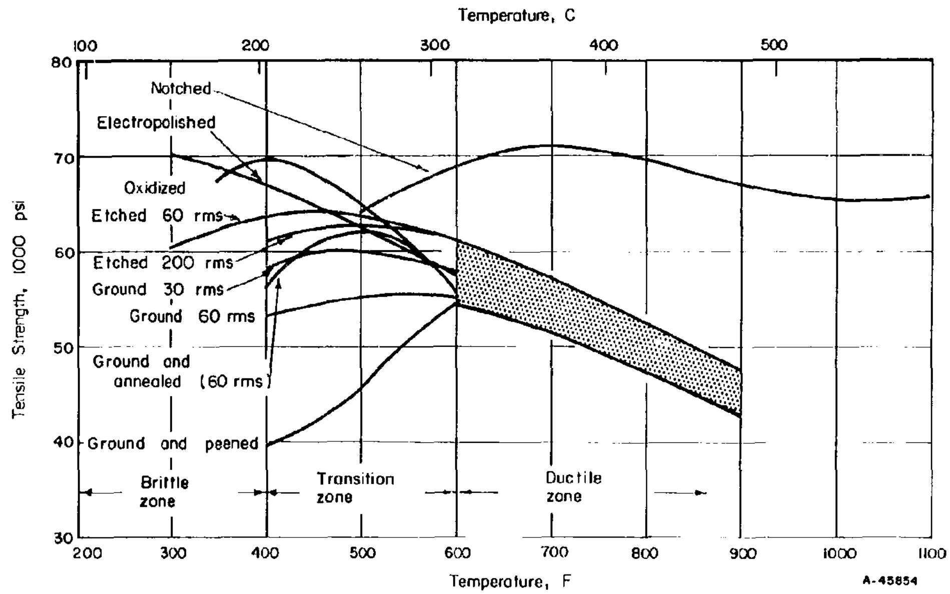


FIGURE A-32. EFFECT OF SURFACE CONDITION ON THE TENSILE STRENGTH OF RECRYSTALLIZED (1 HOUR 3500 F) POWDER-METALLURGY TUNGSTEN ROD (0.170 INCH)[19]

Crosshead speed 0.2 inch per minute.

Analyses 0.0004% O, 0.0076% C, <0.0001% N, 0.0035% Al, 0.0010% Ni, 0.0025% Fe, 0.0010% Si, and 0.0010% S.

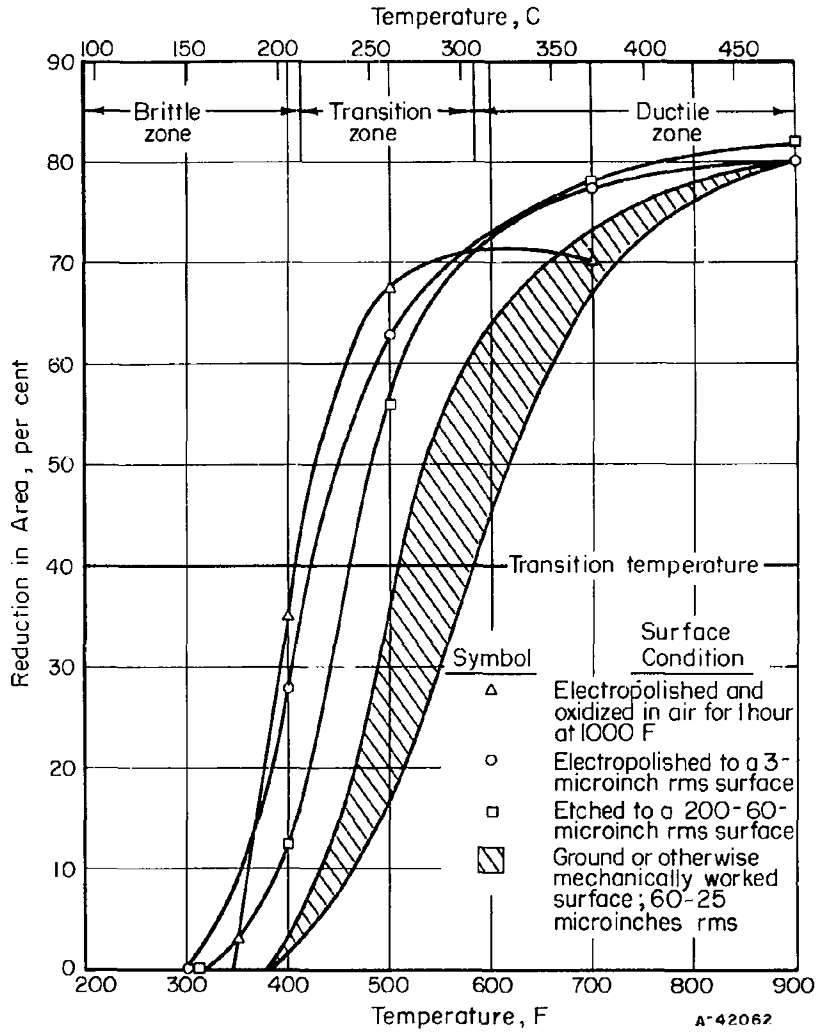


FIGURE A-33. EFFECT OF SURFACE CONDITION ON THE LOW-TEMPERATURE DUCTILITY OF RECRYSTALLIZED (1 HOUR 3500 F) POWDER-METALLURGY TUNGSTEN ROD (0.170 INCH)[19]

Crosshead speed - 0.2 in./min.

Analyses 0.0004% O, 0.0076% C, <0.0001% N, 0.0035% Al, 0.0010% Ni, 0.0025% Fe, 0.0010 Si, and 0.0010% S.

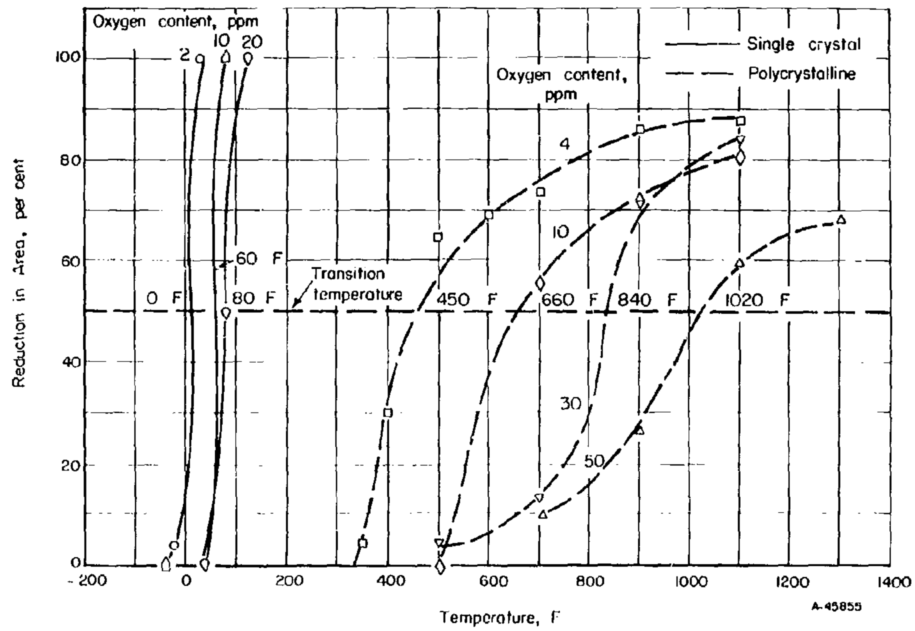


FIGURE A-34. EFFECT OF OXYGEN ON THE DUCTILITY OF POWDER-METALLURGY TUNGSTEN ROD (0.125 INCH)(33)

Test rate 0.005 inch per minute to 0.2 per cent yield, then 0.05 inch per minute to fracture.

	Base Material								
Element	C	O	Mo	Fe	K	Al	Si	Cr	Ni
Amount Present, ppm	8	4	20	10	20	10	10	10	10

TABLE A-17. EFFECT OF FINAL ROLLING REDUCTION ON THE RECRYSTALLIZATION TEMPERATURE OF ARC-MELTED TUNGSTEN[a][11]

Reduction per cent	Temperature, F Initiation of Recrystallization	50 Per Cent Recrystallization	Complete Recrystallization
99	1900	2150	2400
92-95	1900	2150	2400
80	2100	2300	2450
60	2200	2350	2600
40	2300	2500	2650

(a) Data for 1 hour at temperature. Analyses 0.0010% C, 0.0008% O, and 0.0004% N.

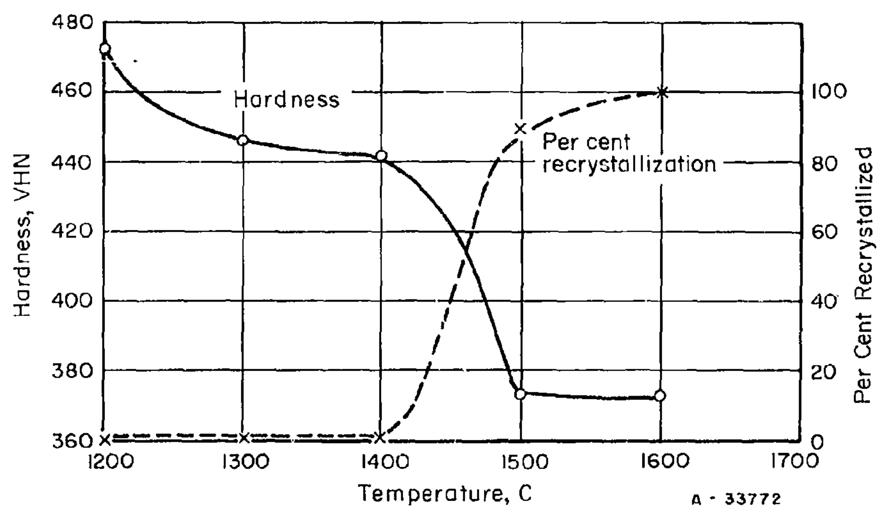


FIGURE A-35. ANNEALING CURVE FOR POWDER-METALLURGY TUNGSTEN BAR[22]

1/4 hour at temperature in an argon atmosphere; air cooled.

Element	Weight Per Cent
C	0.001
O	0.0005
N	<0.001
H	<0.0001

References

(1) Proposed Tentative Specification for Unalloyed Sintered Tungsten Billets, Bars, Rods, and Preforms for Forging, Sixth Draft, American Society for Testing and Materials (April 16, 1963).

(2) "Development of Extrusion Processes for Tungsten", Wah Chang Corp., First Interim Report on Contract AF 33(600)-42395 (March, 1961).

(3) Ratiff, J. L., and Ogden, H. R., "A Compilation of the Tensile Properties of Tungsten", Battelle Memorial Institute, DMIC Memorandum 157 (September 11, 1962).

(4) "Tungsten Sheet Rolling Program", Universal-Cyclops Steel Corp., AMC Interim Report 7-827 (I) on Contract AF 33(600)-41917 (December, 1960).

(5) Sutherland, E. C., and Klopp, W. D., "Observations of Properties of Sintered Wrought Tungsten Sheet at Very High Temperatures", National Aeronautics and Space Administration, NASA TN D-1310 (February, 1963).

(6) Private Communication, Battelle Memorial Institute.

(7) Metals Handbook, Properties and Selection of Metals, 8th Edition, American Society for Metals, Cleveland (1961), Vol 1, pp 1225-26.

(8) Metallwerk Plansee, G. m. b. H., Reutte, Tirol, "Tungsten", Druckschrift 150. 4. 59, Tiroler Graphik, Innsbruck, Innrain 27-29.

(9) Agte, C., and Vacek, J., Wolfram and Molybdän, Akademie-Verlag (1959).

(10) "Tungsten Strand for Vacuum Metallizing", Technical Information Bulletin, Sylvania Electric Products, Inc.

(11) Ogden, H. R., "Department of Defense Refractory Metals Sheet-Rolling Program", Status Report No. 2, Battelle Memorial Institute, DMIC Report 176 (October 15, 1962).

(12) Rabensteine, A. S., "Mechanical Properties of Commercially Pure Sintered Tungsten Alloy Sheet From Room Temperature to 4500 F", Marquardt Corp., Contract No. AF 33(657)-8706, Report 281-2Q-3 (December 1, 1962).

(13) Parechanian, H., "Design Data Manual on Tungsten", Hughs Tool Co., Aircraft Division, Summary Report on Contract AF 33(616)-7385, Report HTC 62-1 (July, 1962).

(14) "Tungsten", Brochure from Sylvania Electric Products, Inc. (1962).

(15) "Thermocouple Alloys", Brochure from Hoskins Manufacturing Co.

(16) "Tungsten Sheet and Plate, Powder Metallurgy, Unalloyed", General Electric Co., Product Data Sheet 1400-C (March 4, 1963).

(17) Hall, R. W., and Sikora, P. F., "Tensile Properties of Molybdenum and Tungsten from 2500 F to 3700 F", NASA Memorandum 3-9-59E, Lewis Research Center (1959).

(18) Silora, P. F., and Hall, R. W., "High Temperature Tensile Properties of Wrought Sintered Tungsten", NASA TN-D-79, Lewis Research Center (1959).

(19) Stephens, J. R., "Effect of Surface Condition on Ductile-to-Brittle Transition Temperature of Tungsten", NASA TN D-676, Lewis Research Center (1961).

(20) Silora, P. F., and Hall, R. W., "Effect of Strain Rate on Mechanical Properties of Wrought Sintered Tungsten Above 2500 F", NASA TN D-1094, Lewis Research Center (1961).

(21) Foyle, F. A., et al., "Initial Investigation of Arc Melting and Extrusion of Tungsten", NASA TN D-269, Lewis Research Center (1960).

(22) Imgram, A. G., et al., "Notch Sensitivity of Refractory Metals", Battelle Memorial Institute, WADD TR 60-278 (April, 1960).

(23) Ratliff, J. L., et al., "Development of a Ductile Tungsten Sheet Alloy", Battelle Memorial Institute, Summary Report on Contract NOw-61-0677-C (1962).

(24) Ratliff, J. L., Battelle Memorial Institute, unpublished data (1962).

(25) "Investigation of the Properties of Tungsten and its Alloys", Union Carbide Metals Co., WADD TR 60-144 (1960).

(26) Sell, H. G., et al., "Physical Metallurgy of Tungsten and Tungsten-Base Alloys", Westinghouse Lamp Division, WADD TR 60-37, Part II (1961).

(27) Glasier, L. F., et al., "Mechanical and Physical Properties of the Refractory Metals, W, Ta, and Mo Above 4000 F", Aerojet-General Corp. (1959).

(28) Bodine, G. C., "Tungsten Sheet Rolling Program", Fansteel Metallurgical Corp., Contract NOw 60-0621-C, Interim Reports 6 and 9 (1961-1962).

(29) Schoenfeld, W. J., "Tungsten Sheet Rolling Program", Universal Cyclops Steel Corp., USAF, Interim Reports 3 and 4 (1962).

(30) Japka, J. E., and Hoppin, G. S., "Roll Forming Tungsten Rocket Nozzles", General Electric Co., Final Report on Contract NOrd 88119.

(31) Pugh, J. W., "Tensile and Creep Properties of Tungsten at Elevated Temperatures", ASTM Proceedings, 57, 906-915 (1957).

(32) Bechtold, J. H., "Flow and Fracture Characteristics of Annealed Tungsten", Transactions ASM, 46, 397-408 (1954).

(33) Stephens, J. R., "Effect of Oxygen on Mechanical Properties of Tungsten", National Aeronautics and Space Administration, NASA TN D-1581 (April, 1963).

(34) Atkinson, R. H. and Staff of Metals Res. Group, Westinghouse Lamp Div., "Physical Metallurgy of Tungsten and Tungsten-Base Alloys", WADD TR 60-37 (May, 1960).

(35) Green, W. V., "Short-Time Creep-Rupture Behavior of Tungsten at 2250 C to 2800 C", Trans. AIME, 215 (December, 1959).

(36) Hum, J.K.Y., and Donlevy, A., "Same Stress-Rupture Properties of Columbium, Molybdenum, Tantalum, and Tungsten Metals and Alloys Between 2400 and 5000 F", Stauffer Metals Co., paper presented at SAE National Aeronautic Meeting, New York (1961).

(37) Foster, L. R., and Stein, B. A., "Tensile Properties and Sheet-Bending Fatigue Properties of Some Refractory Metals at Room Temperature", National Aeronautics and Space Administration, NASA TN D-1592 (January, 1963).

(38) Magnusson, A. W., and Baldwin, W. M., "Low Temperature Brittleness", J. Mech. Phys. Solids, 5, 172-181 (1957).

(39) Lement, B. S., et al., "Substructure and Mechanical Properties of Refractory Metals", Contract No. AF 33(616)-6838, WADD TR-61-181, Part II (October, 1962).

(40) Weiss, V., et al., "Air Weapons Materials Application Handbook Metals and Alloys", Syracuse University Research Institute, AFSC Supplement I to ARDC-TR-59-66 (August, 1962).

"Doped" Tungsten

1. Identification of Material

   a. Designation: many, depending upon individual supplier

   b. Chemical composition: doped tungsten consists of the addition of small amounts of alkaline silicates and aluminum oxide, most of which, except the latter, evaporate in sintering to leave a distillation residue(1); this residue is on the order of 0.02 per cent(2)

   c. Forms available: sheet, foil, and wire(1, 3)

2. Physical Properties

   a. Melting point: 6170 F (estimated to be the same as that for unalloyed tungsten)

   b. Density: 0.697 $lb/in.^3$ (estimated to be the same as that for unalloyed tungsten)

   c. Electrical resistivity: Figure A-36

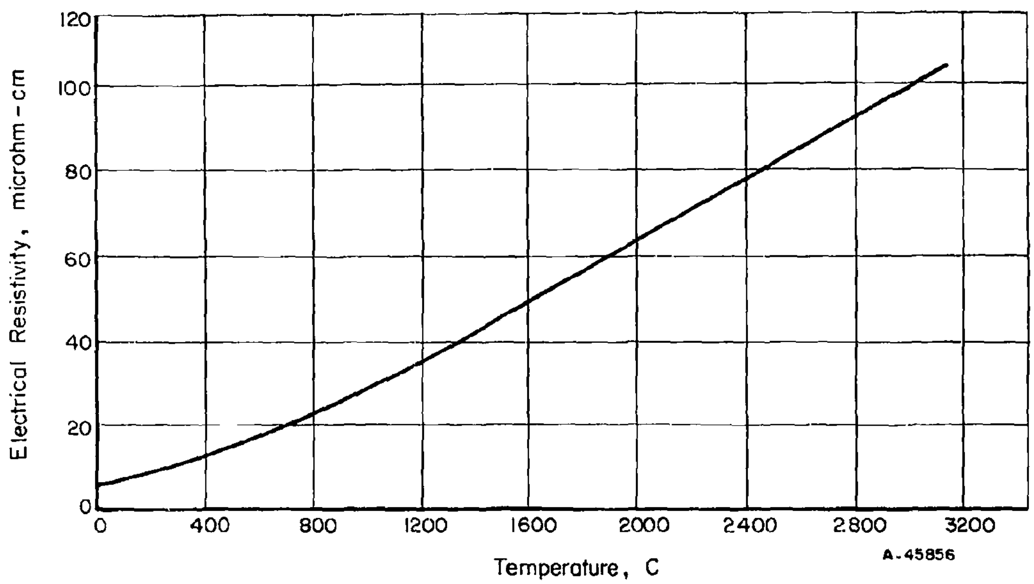


FIGURE A-36. ELECTRICAL RESISTIVITY OF GENERAL ELECTRIC 218 DOPED TUNGSTEN WIRE [3]

3. Mechanical Properties

a. Tensile Properties at Room Temperature

Ultimate tensile strength: Table A-18
Figures A-37 through A-39

Tensile yield strength: Table A-18

Elongation: Table A-18
Figures A-40 and A-41

b. Effect of Temperature on Tensile Properties

Ultimate tensile strength: 22,500 psi at 2500 F for sintered, swaged, and annealed (1/2 hour at 2730 F) material[5]

Figure A-42

Elongation: Figure A-43

c. Creep and Stress-Rupture Properties

For sintered, swaged, and annealed (1/2 hour, 2730 F) material tested at 2500 F[5]

Stress, 1000 psi	Minimum Creep Rate, per cent/hour	Rupture Life, hours
15.0	0.070	105
12.5	0.162	49
10.0	0.04	140

d. Other Selected Mechanical Properties

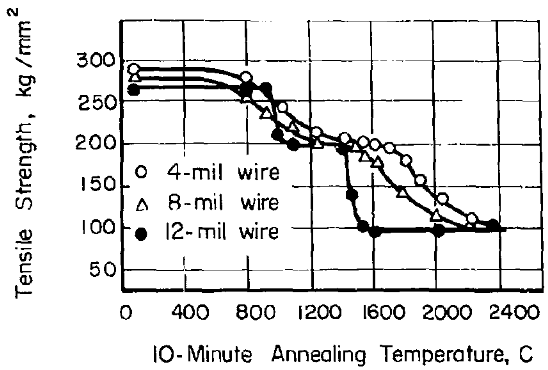
Hardness: for General Electric 218 "doped" tungsten wire (8 mil)[4]

	3-Minute Annealing Temperature, C				
	1750	2000	2240	2750	2850
RH Hardness, DPH	544	435	396	391	391

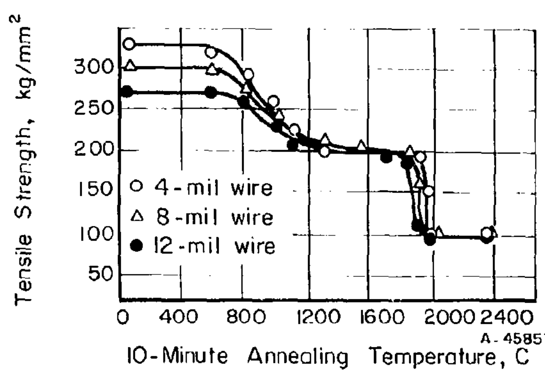
TABLE A-18. TENSILE PROPERTIES OF DOPED TUNGSTEN WIRE (8 MIL) AT ROOM TEMPERATURE[a][4]

Property	As Drawn	3-Minute Annealing Temperature, C					
		1750	2000	2240	2500	2750	2850
Tensile Strength, 1000 psi	400	276	197	193	193	180	163
Yield Strength, 1000 psi	326	270	192	190	193	180	163
Elongation, per cent	0.2	0.3	[illegible]	0.2	0	0	0

(a) Test rate 0.1 inch per inch per minute.



Impurity	Weight Per Cent
Mo	0.01
Fe	0.005
SiO_2	0.016
Al_2O_3	0.004



Impurity	Weight Per Cent
Mo	0.02
Fe	0.05
SiO_2	0.01
Al_2O_3	0.006
Mg	0.001
Ni	0.002

FIGURE A-37. EFFECT OF ANNEALING TEMPERATURE ON THE ROOM-TEMPERATURE TENSILE STRENGTH OF DOPED TUNGSTEN WIRES(2)

Note: Analyses on powder.

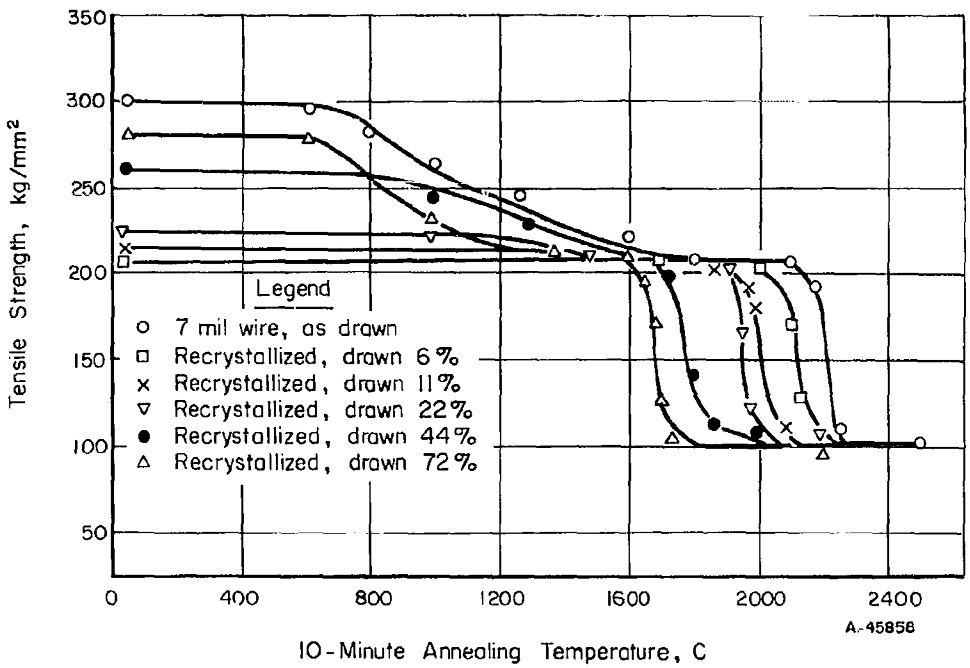
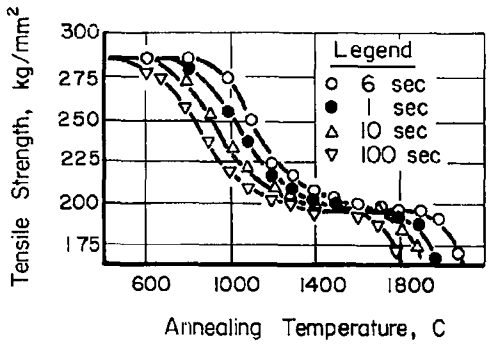


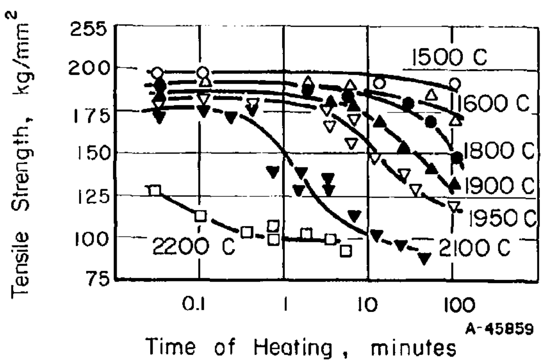
FIGURE A-38. EFFECT OF REDUCTION AND ANNEALING TEMPERATURE ON THE ROOM-TEMPERATURE TENSILE STRENGTH OF DOPED TUNGSTEN WIRES(2)

Impurity	Weight Per Cent
Mo	0.04
Fe	0.002
SiO_2	0.08
Al_2O_3	0.010
Ni	0.001

Note: Analyses on powder.



a. For primary recrystallization



b. For secondary recrystallization

FIGURE A-39. EFFECT OF ANNEALING TIME AND TEMPERATURE ON THE ROOM-TEMPERATURE TENSILE STRENGTH OF DOPED TUNGSTEN WIRE (8 MIL)[2]

Impurity	Weight Per Cent
Mo	0.05
Fe	0.013
SiO_2	0.16
Al_2O_3	0.006
Ni	0.001

Note: Analyses on powder.

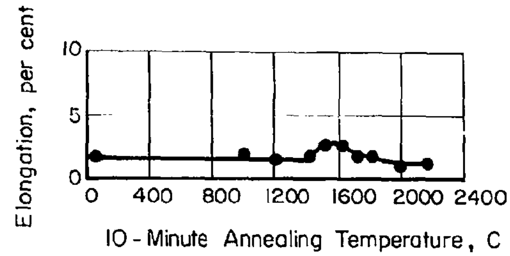


FIGURE A-40. EFFECT OF ANNEALING TEMPERATURE ON THE ROOM-TEMPERATURE DUCTILITY OF DOPED TUNGSTEN WIRE (8 MIL)[2]

Impurity	Weight Per Cent
Mo	0.05
Fe	0.013
SiO_2	0.16
Al_2O_3	0.006
Ni	0.001

Note: Analyses on powder.

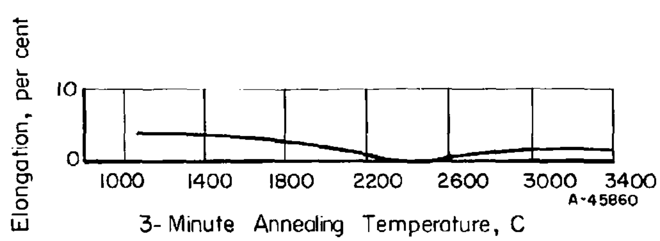


FIGURE A-41. EFFECT OF ANNEALING TEMPERATURE ON THE ROOM-TEMPERATURE DUCTILITY OF GENERAL ELECTRIC 218 DOPED TUNGSTEN WIRE (7 MIL)[3]

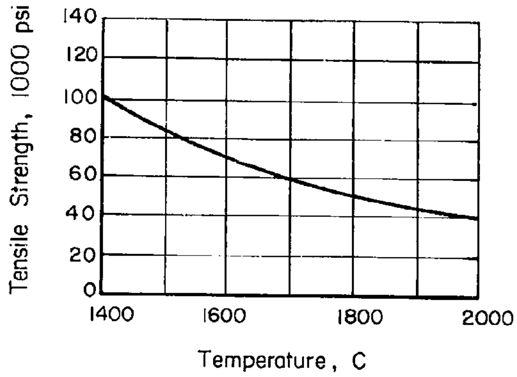


FIGURE A-42. EFFECT OF TEMPERATURE ON THE TENSILE STRENGTH OF GENERAL ELECTRIC 218 DOPED TUNGSTEN WIRE (8 MIL)[3]

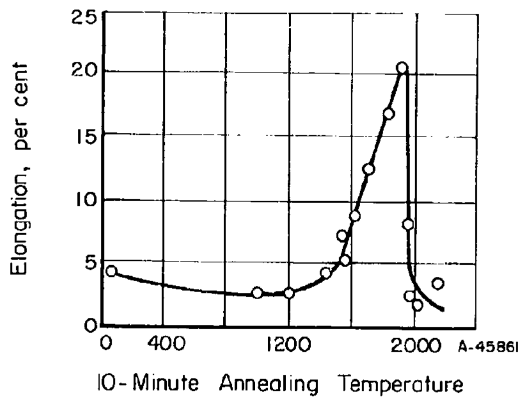


FIGURE A-43. EFFECT OF ANNEALING TEMPERATURE ON THE 200 C DUCTILITY OF DOPED TUNGSTEN WIRE (8 MIL)[2]

Impurity	Weight Per Cent
Mo	0.05
Fe	0.013
SiO_2	0.16
Al_2O_3	0.006
Ni	0.001

Note: Analyses on powder.

4. Metallurgical Properties

a. Fabricability: sintered slabs can be forged at 2700 to 3300 F and warm rolled to sheet (0.040 inch) with intermediate stress-relieving treatments (2280 F) at each 50 per cent reduction level; cold rolling is used below 0.040 inch to produce thin sheet or foil[1]; wire drawing is conducted at 1075 F[2]

b. Transition temperature: highly worked wire has useful room-temperature ductility[2, 3]

c. Stress-relief temperature: 10 minutes at 1800 to 2200 F[2], 3 minutes at 2900 F[4], for as-heavily-drawn wire

d. Recrystallization temperature: 10 to 100 minutes at 3550 F or above[2], 3 minutes at 4050 F[4], for as-heavily-drawn wire

References

(1) "Refractory Alloy Foil Rolling Development Program", Metals Center, E. I. du Pont de Nemours and Co., Inc., Contract No. AF 33(657)-8912, Interim Report No. 1 (October, 1962).

(2) Davis, G. L., "Recrystallization of Tungsten Wires", Metallurgia, 58, 177-184 (October, 1958).

(3) "Tungsten-Rhenium Alloy Wire", General Electric Co., Product Data Sheet 1300-C (January 22, 1962).

(4) Pugh, J. W., Amra, L. H., and Hurd, D. T., "Properties of Tungsten-Rhenium Lamp Wire", Trans. ASM, 55 (3) (September, 1962).

(5) Atkinson, R. H., and Staff of Metals Research Group, Westinghouse Lamp Div., "Physical Metallurgy of Tungsten and Tungsten-Base Alloys", WADD TR 60-37 (May, 1960).

W-0.38TaC

1. Identification of Material

   a. Chemical composition: W-0.38TaC

   b. Forms available: ingot and fabricated shapes on a best efforts basis

2. Physical Properties

   a. Melting point: 6170 F (estimated to be the same as that for unalloyed tungsten)

   b. Density: 0.696 $lb/in.^3$ (calculated)[1]

3. Mechanical Properties

   a. Effect of Temperature on Tensile Properties

      Ultimate tensile strength: Table A-19

      Tensile yield strength: Table A-19

      Elongation: Table A-19

      Reduction in area: Table A-19

   b. Creep and Stress-Rupture Properties

      Figure A-44

TABLE A-19. HIGH-TEMPERATURE TENSILE PROPERTIES OF W-0.38TaC ROD(a)(2,3)

Condition	Temperature, F	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Uniform Elongation, per cent	Total Elongation, per cent	Reduction in Area, per cent
			Extruded			
Stress relieved	2500	40-44	40-42	1	12-14	84-87
Recrystallized	2500	20-22	8-9	18-21	>39->45	>32->40
Stress relieved	2700	32-35	31-34	1	13-27	70-81
Recrystallized	2700	17	8	13-15	25	23-26
Recrystallized	3000	11-17	5-10	11-16	31->39	>27->36
			Swaged			
Stress relieved	3000	>32	<32	--	>2	>2
Recrystallized	3000	19-20	12	16-18	>38->39	>33->50
As swaged to various reductions	3000	22-32	16-26	--	7-33	16-42

(a) Test rate 30 per cent per hour.

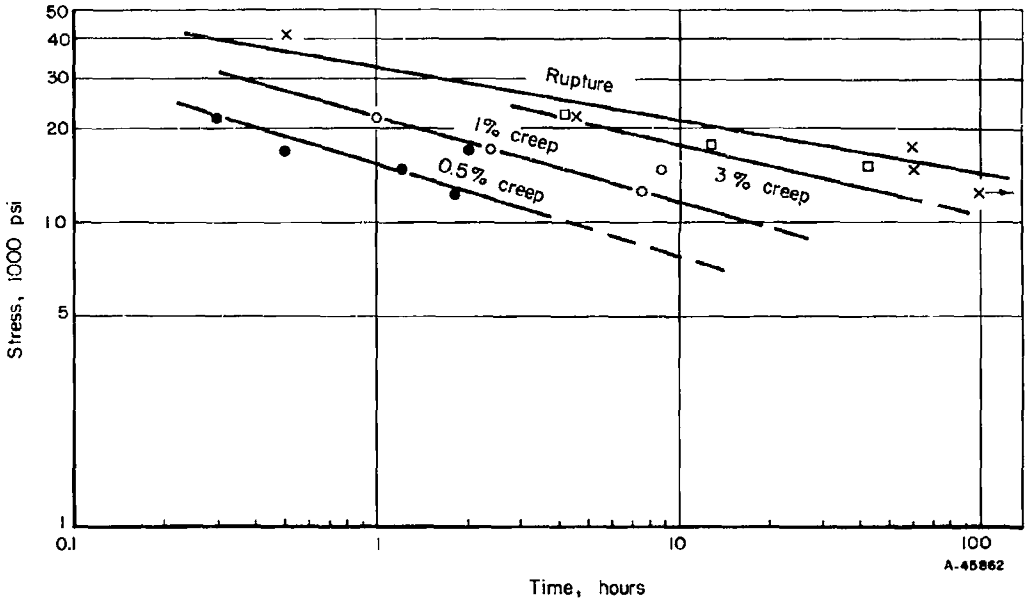


FIGURE A-44. CREEP AND STRESS-RUPTURE PROPERTIES OF W-0.38TaC AT 2800 F(4)

4. Metallurgical Properties

   a. Fabricability: sintered billets can be readily extruded at 4000 F, followed by large total swaging reductions at 3090 F[3]

   b. Stress-relief temperature: 30 minutes at 2370 F for extruded and swaged (77 per cent) material[3]

   c. Recrystallization temperature: Figures A-45 and A-46

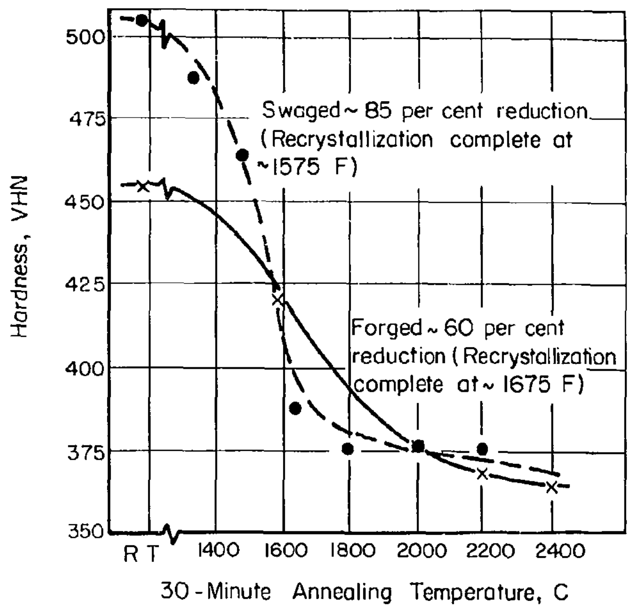


FIGURE A-45. EFFECT OF ANNEALING TEMPERATURE ON THE HARDNESS OF W-0.38 TaC(4)

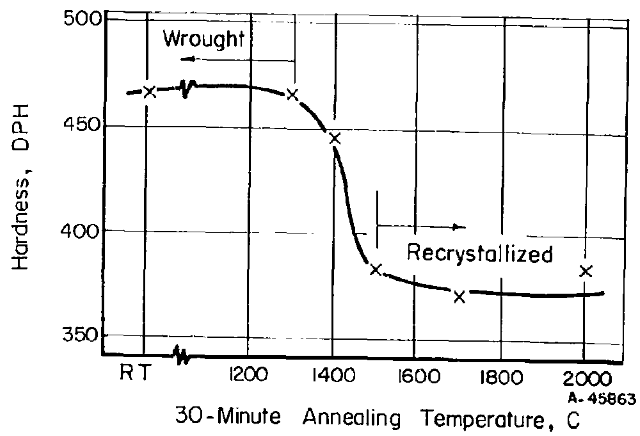


FIGURE A-46. ANNEALING BEHAVIOR OF EXTRUDED AND SWAGED W-0.38 TaC(3)

Extruded: 4000 F
Swaged: 77 per cent at 3090 F

References

(1) Maykuth, D. J., and Ogden, H. R., "What Refractory Metal Shall I Use ... for Ultrahigh-Temperature Applications (Above 1800°F)?", Metal Progress (October, 1961).

(2) Sell, H. G., et al., "The Physical Metallurgy of Tungsten and Tungsten Base Alloys", Westinghouse Lamp Division, Contract No. AF 33(657)-8247, Third Quarterly Progress Report (March 12, 1963).

(3) Sell, H. G., et al., "Physical Metallurgy of Tungsten and Tungsten Base Alloys", Westinghouse Lamp Division, WADD-TR-60-37 (Part III) (November, 1962).

(4) Sell, H. G., et al., "Physical Metallurgy of Tungsten and Tungsten Base Alloys", Westinghouse Lamp Division, WADD-TR-60-37 (Part II) (May, 1961).

$W-1ThO_2$

1. Identification of Material

    a. Chemical composition: $W-1ThO_2$

    b. Forms available: rod, strip, and wire

2. Physical Properties

    a. Melting point: 6170 F (estimated to be the same as that of unalloyed tungsten)

    b. Density: 0.690 lb/in.^{3} (calculated)[1]

3. Mechanical Properties

    a. Effect of Temperature on Tensile Properties

        Ultimate tensile strength: Figure A-47

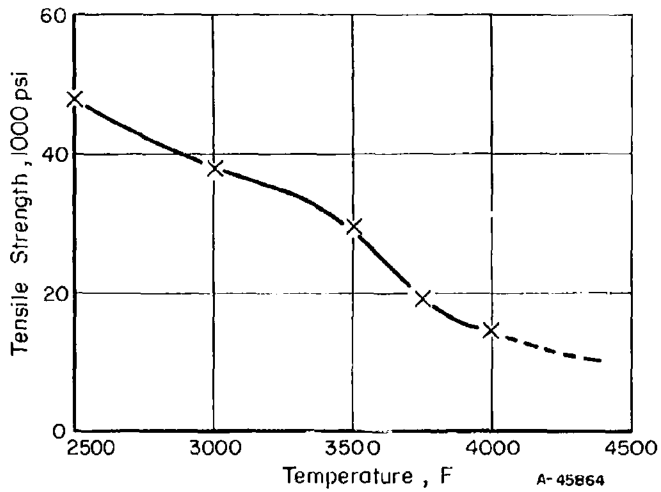


FIGURE A-47. EFFECT OF TEMPERATURE ON THE TENSILE STRENGTH OF SINTERED AND SWAGED W-1ThO$_2$ ROD[2]

4. Metallurgical Properties

a. Fabricability: excellent rolling behavior has been obtained by breakdown rolling of sintered compacts at 3270 F, intermediate rolling at 2550 to 2910 F, and final finish rolling at 2190 F[3]

b. Transition temperature: for sheet (0.035 inch)[3]

1-Hour Annealing Temperature, F	Grain Size, grains/mm^2	Transition Temperature, F	
		8T	4T
1830	Wrought	345	345
2190	Wrought	435	435
3270	1425	660	690

c. Stress-relief temperature: 1 hour at 2190 to 2370 F[3]

d. Recrystallization temperature: 1 hour at 2910 F for material reduced 80 per cent[3]

References

(1) Maykuth, D. J., and Ogden, H. R., "What Refractory Metal Shall I Use . . .for Ultrahigh-Temperature Applications (Above 1800°F)?", Metal Progress (October, 1961).

(2) Hall, R. W., Sikora, P. F., and Ault, G. M., "Mechanical Properties of Refractory Metals and Alloys Above 2000 F", paper presented at AIME Refractory Metals Symposium, Detroit (May 26, 1960).

(3) Ratliff, J. L., et al., "Development of a Ductile Tungsten Sheet Alloy", Battelle Memorial Institute, Contract No. NOw 61-0677-C (May 26, 1962).

$W-2ThO_2$

1. Identification of Material

   a. Chemical composition: $W-2ThO_2$

   b. Forms available: rod, strip, and wire

2. Physical Properties

   a. Melting point: 6170 F (estimated to be the same as that for unalloyed tungsten)

   b. Density: 0.683 lb/in.^{3} (calculated)[1]

3. Mechanical Properties

   a. Effect of Temperature on Tensile Properties

      Ultimate tensile strength: Table A-20
      Figures A-48 and A-49

      Tensile yield strength: Table A-20

      Elongation: Table A-20

      Reduction in area: Table A-20

   b. Creep and Stress-Rupture Properties

      For annealed rod[5]

Stress, 1000 psi	Time to Rupture, hours
15.0	4.4
12.5	5.7
7.5	10.5

Figure A-50

TABLE A-20. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF W-$2ThO_2$ ROD

Temperature, F	Condition	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation, per cent	Reduction in Area, per cent	Reference
2500	Worked 60 per cent	37.0	35.0	20	62	(2)
	Worked 80 per cent	42.0	41.0	12	73	(2)
2700	Annealed 1/2 hour 2910 F	33.0	32.0	14	38	(2)
	Annealed 1/2 hour 3810 F	32.0	31.5	17	51	(2)
3000	Annealed 1/2 hour 2910 F	27.0	21.0	4	16	(2)
	Annealed 4 hours 3540 F	15.4	10.9	22	23	(3)
	Annealed 1/2 hour 3990 F	14.8	10.0	22	19	(3)

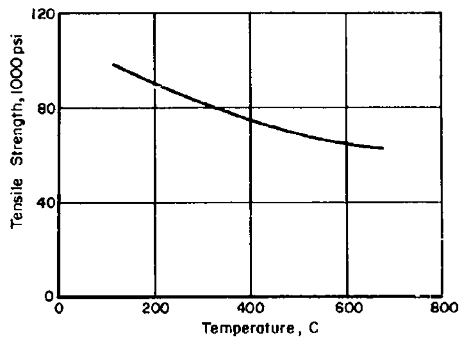


FIGURE A-48. EFFECT OF LOW TEMPERATURE ON THE TENSILE STRENGTH OF ANNEALED W-2ThO_2 ROD[3]

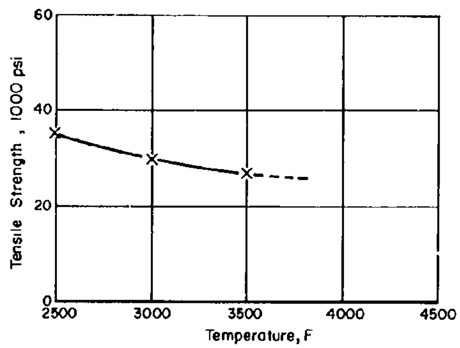


FIGURE A-49. EFFECT OF HIGH TEMPERATURE ON THE TENSILE STRENGTH OF SINTERED AND SWAGED W-2ThO_2 ROD[4]

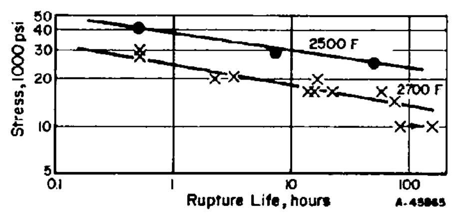


FIGURE A-50. STRESS-RUPTURE PROPERTIES OF ANNEALED W-2ThO_2 ROD[2]

Metallurgical Properties

a. Fabricability: excellent rolling behavior has been obtained by breakdown rolling of sintered compacts at 3270 F, intermediate rolling at 2550 F to 2910 F, and final finish rolling at 2190 F[6]; swaging and forging can readily be accomplished at 3090 F[7]

b. Transition temperature: for sheet (0.035 inch)[6]

1-Hour Annealing Temperature, F	Grain Size, grains/mm^2	Transition Temperature, F	
		8T	4T
1830	Wrought	345	345
2190	Wrought	365	365
3270	2125	615	660

Figure A-51

c. Stress-relief temperature: 1 hour at 2190 to 2370 F[6]

d. Recrystallization temperature: 1 hour at 3090 F for material reduced 80 per cent[6]; 1/2 hour at 4350 F[2]

Figure A-52

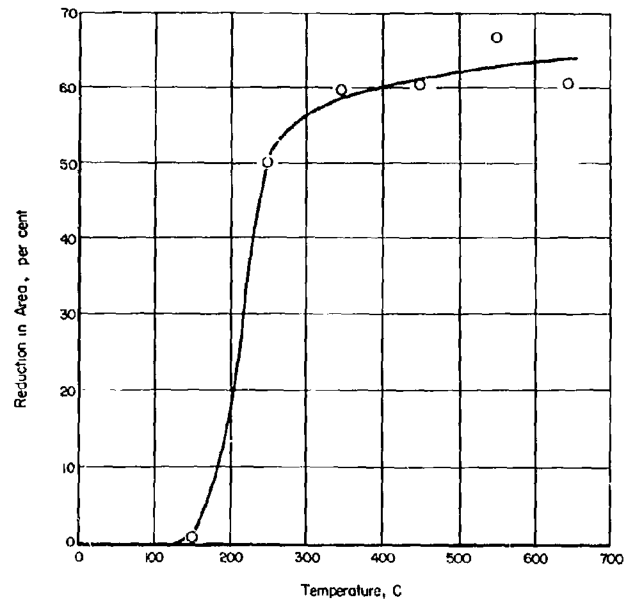


FIGURE A-51. TRANSITION BEHAVIOR OF ANNEALED (1/2 HOUR 2730 F) W-2ThO_2 ROD (0.179 INCH)[7]

Strain rate 30 per cent per hour.

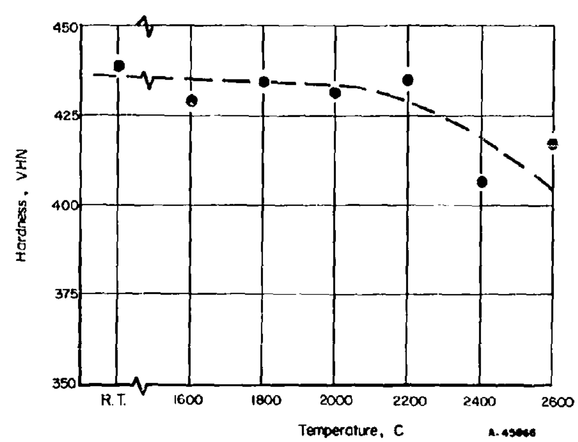


Figure A-52. EFFECT OF 1/2-HOUR ANNEALING TEMPERATURE ON THE HARDNESS OF W-2ThO_2 ROD[2]

References

(1) Maykuth, D. J., and Ogden, H. R., "What Refractory Metal Shall I Use . . . for Ultrahigh-Temperature Applications (Above 1800°F)?", Metal Progress (October, 1961).

(2) Sell, H. G., et al., "Physical Metallurgy of Tungsten and Tungsten-Base Alloys", Westinghouse Lamp Division, WADD TR 60-37, Part II (May, 1961).

(3) Sell, H. G., et al., "The Physical Metallurgy of Tungsten and Tungsten-Base Alloys", Westinghouse Lamp Division, Third Quarterly Progress Report (March 12, 1963).

(4) Hall, R. W., Sikora, P. F., and Ault, G. M., "Mechanical Properties of Refractory Metals and Alloys Above 2000 F", paper presented at AIME Refractory Metals Sumposium, Detroit (May 26, 1960).

(5) Sell, H. G., et al., "Physical Metallurgy of Tungsten and Tungsten-Base Alloys", Westinghouse Lamp Division, WADD TR 60-37, Part III (November, 1962).

(6) Ratliff, J. L., et al., "Development of a Ductile Tungsten Sheet Alloy", Battelle Memorial Institute, Contract No. NOw 61-0677-C (May 26, 1962).

(7) Atkinson, R. H., and Staff of Metals Research Group, Westinghouse Lamp Div., "Physical Metallurgy of Tungsten and Tungsten-Base Alloys", WADD TR 60-37, Part I (May, 1960).

W-0.6Cb

1. Identification of Material

   a. Chemical composition: W-(0.5-0.6)Cb

   b. Forms available: ingot and fabricated shapes available from suppliers on a best efforts basis

2. Physical Properties

   a. Melting point: ~6160 F[(1)]

   b. Density: 0.692 lb/in.^{3} (calculated)

3. Mechanical Properties

   a. Effect of Temperature on Tensile Properties

      Ultimate tensile strength: Tables A-21 and A-22
      Figure A-53

      Tensile yield strength: Tables A-21 and A-22
      Figure A-53

      Elongation: Tables A-21 and A-22
      Figure A-53

      Reduction in area: Tables A-21 and A-22
      Figure A-53

   b. Creep and Stress-Rupture Properties

      For material as extruded (3550 F) and tested at 3000 F[(a)(5)]

Stress, 1000 psi	Time to Rupture, hours	Elongation, per cent	Reduction in Area, per cent
25.0	0.8	42.7	92
20.0	3.8	53.3	89
15.0	32.45	51.2	89.6

(a) Analyses 0.0010% O, 0.0120% C, <0.0001% H, 0.0009% N, <0.0010% Al, 0.0005% Fe, 0.0005% Ni, <0.0020% Si, and 0.52% Cb.

TABLE A-21. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF ARC-CAST W-0.6 Cb

Temperature, F	Condition	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation, per cent	Reduction in Area, per cent
	Reference 2, 0.02 Inch per Minute Crosshead Speed				
2800	As extruded, 3400 F[a]	49.2	45.5	18	92
3000	As extruded, 3400 F[a]	42.5	38.4	15	99
3000	Annealed 1 hour 2900 F[a]	24.8	20.7	33	95
	Reference 3, 0.02 Inch per Minute Crosshead Speed				
3000	As swaged, 2650 F[b]	60.6	50.0	20	82
	Reference 4, 300 Per Cent per Hour				
3000	As swaged, 2800 F[c]	42.74	41.4	13.3	84.2
3000	As swaged, 2800 F[d]	45.0	43.5	14.0	89.1
	Reference 5, 0.02 Inch per Minute Crosshead Speed				
3000	As extruded, 3550 F[e]	38.21	35.075	32.6	80
3250	As extruded, 3550 F[e]	22.64	18.66	46.9	63.2
3500	As extruded, 3550 F[e]	13.04	7.71	55.6	64.7
4000	As extruded, 3550 F[e]	7.25	4.5	81.7	90

Note:

Analyses

Element	Amount Present, ppm (a)	(b)	(c)	(d)	(e)
C	180	100	10	18	120
O	90	40	17	9	10
H	<10	--	1	<1	<1
N	180	--	22	14	9
Al	--	--	--	10	<10
Ca	--	--	--	<10	--
Cb	0.58%	0.57%	0.68%	0.74%	0.52%
Cr	--	--	--	<10	--
Cu	--	--	--	<10	--
Fe	180	--	--	10	5
Mg	--	--	--	<10	--
Mn	--	--	--	<10	--
Mo	300	1000	--	25	--
Ni	--	--	--	--	5
Si	--	--	-	10	<20
Ta	50	--	--	--	--

TABLE A-22. EFFECT OF FORGING TEMPERATURE AND REDUCTION ON THE 3000 F TENSILE PROPERTIES OF W-0.6Cb[6]

Forging Temperature, F	Reduction, per cent	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation, per cent	Reduction in Area, per cent
2000	20	46.6	43.6	9.3	9.7
2000	40	42.0	40.5	3.2	14.2
2400	20	41.8	39.2	5.0	45.9
2400	60	58.1	53.6	7.2	71.2

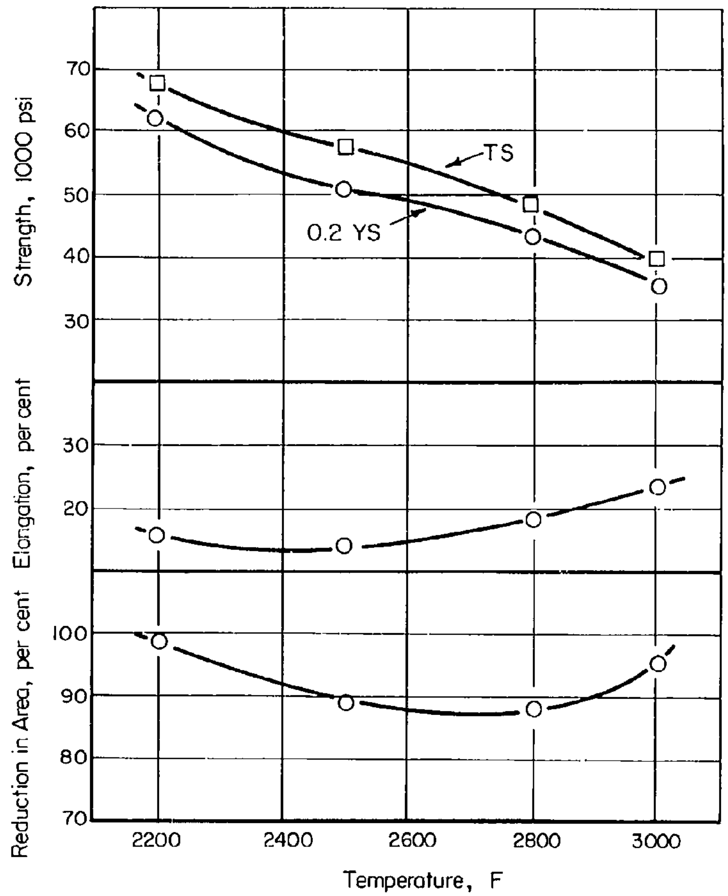


FIGURE A-53. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF ARC-CAST AND SWAGED (3000 F) W-0.6Cb[2]

Crosshead speed 0.02 inch per minute.

Analyses 0.018% C, 0.009% O, <0.0010% H, 0.018% N, 0.58% Cb, 0.03% Mo, 0.005% Ta, and 0.018% Fe.

4. Metallurgical Properties

a. Fabricability: extrusion temperatures of 3400 to 3800 F have been used to convert arc-cast billets into wrought form[2, 4, 5]; some problems have been encountered in high-temperature forging[4]; swaging is performed at 2650 to 3000 F[3,4,5]

b. Transition temperature: 575 F for arc-cast and extruded W-0.52 Cb tested at 0.02 inch per minute crosshead speed[7]

c. Stress-relief temperature: 1 hour at 2700 to 2900 F for material reduced 55 per cent by forging[4]

d. Recrystallization temperature: 1 hour at 3100 to 3200 F for material reduced 55 per cent by forging[4]; 1 hour at 3400 F for extruded material[6]

References

(1) English, J. J., "Binary and Ternary Phase Diagrams of Columbium, Molybdenum, Tantalum, and Tungsten", Battelle Memorial Institute, DMIC Report 152 (April 28, 1961).

(2) McKinsey, C. R., et al., "Investigation of Tungsten-Tantalum-Columbium-Base Alloys", Union Carbide Metals Co., ASD TR 61-3 (July, 1961).

(3) Metals Research Laboratories, Union Carbide Metals Company, "Investigation of the Properties of Tungsten and Its Alloys", WADD TR 60-144 (May, 1960).

(4) Reiman, G. A., "Vacuum Arc Melting of Tungsten +0.6 Columbium", Westinghouse Electric Corp., ASD-TDR-63-296 (April, 1963).

(5) Lake, F. N., Breznyak, E. J., and Doble, G. S., "Tungsten Forging Development Program", Thompson Ramo Wooldridge Inc., Contract No. AF 33(600)-41629, AFSC Interim Report 7-797 (IV) (May, 1961).

(6) Carnahan, D. R., and Viscanti, J. A., "The Extrusion, Forging, Rolling, and Evaluation of Refractory Alloys", Westinghouse Electric Corp., ASD-TDR-62-670 (October, 1962).

(7) Lake, F. N., and Breznyak, E. J., "Tungsten Forging Development Program", Thompson Ramo Wooldridge Inc., Contract No. AF 33(600)-41629, AMC Interim Report 7-797 (III) (March, 1961).

W-2Mo

1. Identification of Material

   a. Chemical composition: W-2Mo

   b. Forms available: ingot and fabricated shapes available from suppliers on a best efforts basis

2. Physical Properties

   a. Melting point: 6125F[1]

   b. Density: 0.685 $lb/in.^3$ (calculated)

3. Mechanical Properties

   a. Tensile Properties at Room Temperature

      Ultimate tensile strength: 40,000 psi for centrifugally arc-cast and stress-relieved material[2]

      Elongation: 0 per cent for centrifugally arc-cast and stress-relieved material[2]

      Reduction in area: 0 per cent for centrifugally arc-cast and stress-relieved material[2]

   b. Effect of Temperature on Tensile Properties

      Ultimate tensile strength: Tables A-23 and A-24

      Tensile yield strength: Tables A-23 and A-24

      Elongation: Tables A-23 and A-24

      Reduction in area: Tables A-23 and A-24

TABLE A-23. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF CENTRIFUGALLY ARC-CAST AND STRESS-RELIEVED BUT NOT MECHANICALLY WORKED W-2Mo(2)

Temperature, F	Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation, per cent	Reduction in Area, per cent
70	40.0	--	0	0
600	45.0	30.0	2	13
850	52.55	26.0	25	22
1000	49.0	27.0	25	35
1500	42.0	31.0	--	--
2000	30.0	--	26	--

TABLE A-24. LOW- AND HIGH-TEMPERATURE TENSILE PROPERTIES OF CENTRIFUGALLY ARC-CAST, EXTRUDED, AND FORGED UNIVERSAL THIN SECTION OF W-2Mo(a)(3)

Temperature, F	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation, per cent	Reduction in Area, per cent
		Semi-Coin Forging		
310	159.701	--	4.6	0
395	140.299	139.801	12.1	9.1
460	133.005	131.733	13.6	29.0
540	124.300	123.800	13.9	33.0
655	115.763	114.286	13.1	35.0
2800	51.0	34.7	23.1	94.1
3000	52.3	44.7	25.6	91.8
3900	8.4	6.4	85.7	94.1
3900	8.8	6.3	96.8	96.5
5000	1.2	--	19.5	50.0
5000	1.8	1.5	22.2	58.6
		Coin Forging		
310	161.194	160.448	4.8	1
400	144.279	143.283	15.1	11.9
540	121.800	121.300	13.8	27.4
655	117.413	116.915	10.6	29.9
3000	52.4	47.1	22.1	78.8
3900	8.3	6.2	91.0	99.1
5000	1.9	1.5	22.5	61.7
5000	1.6	--	23.0	52.8

(a) Test rate 0.02 inch per minute crosshead speed.

4. Metallurgical Properties

a. Fabricability: centrifugally arc-cast cylindrical shapes or rectangular slabs can be rolled directly to heavy-gage sheet at temperatures as low as 1830 F; subsequent hot-cold rolling can be used to produce thin gage sheet[2]; significantly higher temperatures are required for successful extrusion and forging[3]

b. Transition temperature: Figures A-54 and A-55

c. Recrystallization temperature: centrifugally arc-cast material cold rolled 30 per cent recrystallizes at 3090 F, producing a grain size of ASTM 6-7[2]

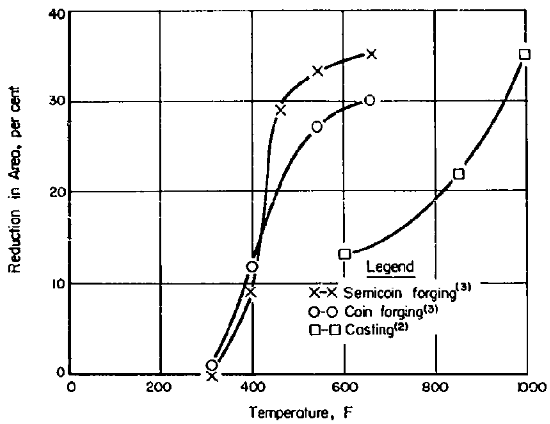


FIGURE A-54. TRANSITION TEMPERATURE OF CENTRIFUGALLY ARC-CAST FORGING AND CASTING STOCK OF W-2Mo

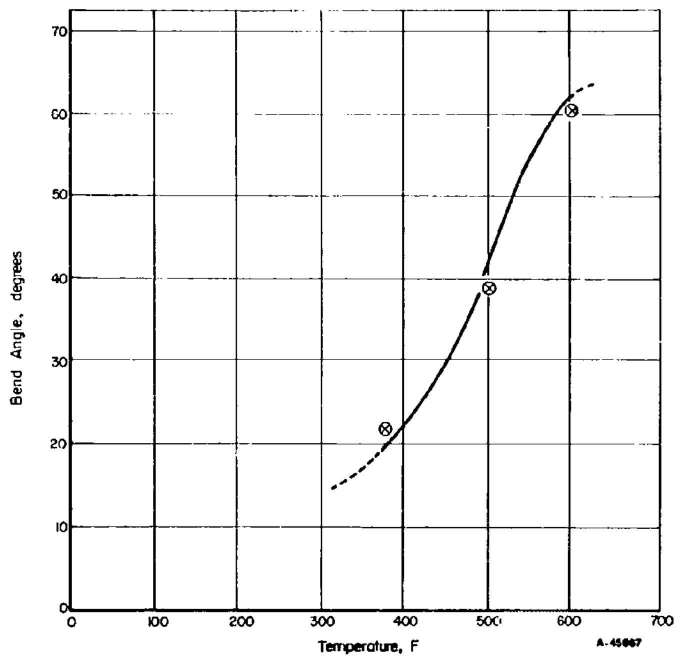


FIGURE A-55. BEND-TRANSITION TEMPERATURE OF CENTRIFUGALLY ARC-CAST AND EXTRUDED W-2Mo(3)

References

(1) Private communication from Oregon Metallurgical Corporation (February, 1961).

(2) "Refractory Alloy Foil Rolling Development Program", Metals Center, E. J. duPont de Nemours and Co., Inc., Contract No. AF 33(657)-8912, Interim Report No. 1 (October, 1962).

(3) Breznyak, E. J., and Lake, F. N., "Tungsten Forging Development Program", Thompson Ramo Wooldridge, Inc., Contract No. AF 33(600)-41629, ASD Interim Report 7-797 (VII) (December, 1962).

W-15Mo

1. Identification of Material

   a. Chemical composition: W-15Mo

   b. Forms available: ingot and fabricated shapes available from suppliers on a best efforts basis

2. Physical Properties

   a. Melting point: 5970F(1)

   b. Density: 0.615 lb/in.^{3} (calculated)

3. Mechanical Properties

   a. Tensile Properties at Room Temperature

      Ultimate tensile strength: Table A-25

      Tensile yield strength: Table A-25

      Elongation: Table A-25

      Reduction in area: Table A-25

      Modulus of elasticity: 59.7×10^6 psi(2)

   b. Effect of Temperature on Tensile Properties

      Ultimate tensile strength: Tables A-26 through A-31
      Figures A-56 and A-57

      Tensile yield strength: Tables A-26 through A-33
      Figures A-56 and A-57

      Elongation: Tables A-26 through A-31
      Figures A-56 and A-57

      Reduction in area: Tables A-26 through A-31
      Figures A-56 and A-57

c. Creep and Stress-Rupture Properties

For material as extruded (3680 F) and tested at 3000 F[a][6]

Stress, 1000 psi	Time to Rupture, hours	Elongation, per cent	Reduction in Area, per cent
25.0	0.65	35.3	73
20.0	3.89	33.0	74
15.0	5.02	45.9	83.4
12.5	12.82	46.7	79

(a) Analyses 0.0022% O, 0.0019% C, <0.0001% H, 0.0010% N, 14.9% Mo, <0.0010% Al, 0.0010% Fe, <0.0001% Ni, and <0.0020% Si.

Figures A-58 and A-59

TABLE A-25. ROOM-TEMPERATURE TENSILE PROPERTIES OF W-15Mo

Form or Condition	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation, per cent	Reduction in Area, per cent	Reference
0.250-inch bar	41.1	--	0	--	(2)
(a)	45.0	--	0	0	(3)
0.105-inch round[b]	181.5(L)	174.5(L)	2.6(L)	1.9(L)	(4)
	164.2(T)	158.6(T)	4.7(T)	3.9(T)	(4)

(a) Centrifugally cast and stress relieved but not mechanically worked.
(b) Test rate 0.02 inch per minute crosshead speed. Properties for highly worked (web) section of universal forging. "L" and "T" relate to grain orientation of original extruded forging bar; forging direction perpendicular to extrusion direction.

TABLE A-26. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF CENTRIFUGALLY ARC-CAST AND STRESS-RELIEVED BUT NOT MECHANICALLY WORKED W-15Mo[3]

Temperature, F	Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation, per cent	Reduction in Area, per cent
70	45	--	0	0
600	42	28	5	5
800	50	22	6	6
1000	50	20	20	20
1500	45	20	15	20
2000	50	--	--	--
2600	42	--	--	--

TABLE A-27. LOW-TEMPERATURE TENSILE PROPERTIES OF EXTRUDED POWDER-METALLURGY W-15Mo[a][5]

Temperature, F	Tensile Strength, 1000 psi	Yield Point, 1000 psi		Elongation, per cent	Reduction in Area, per cent
		Lower	Upper		
390	85.6	--	--	0	0
500	88.6	--	--	0	0
545	99.5	--	--	0	0
580	92.5	--	--	0.3	0
615	100.0	86.6	96.0	27	72
715	74.6	77.1	102.0	1.3	5
385	82.1	--	--	0	0.3
510	103.5	87.6	104.0	59	19
615	95.5	89.6	102.0	68	24

(a) Data for two extrusions. Test rate 0.02 inch per minute crosshead speed.

TABLE A-28. HIGH-TEMPERATURE TENSILE PROPERTIES OF ARC-CAST AND EXTRUDED W-15Mo[(a)(6)]

Temperature, F	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation, per cent	Reduction in Area, per cent
3000	36.0	34.5	27.8	78
3250	24.45	23.5	34.9	80
3500	11.19	8.06	85	95
4000	5.57	4.08	125	97

(a) Extruded at 3680 F. Test rate 0.02 inch per minute crosshead speed. Analyses 0.0022% O, 0.0019% C, <0.0001% H, 0.0010% N, 14.90% Mo, <0.0010% Al, 0.0010% Fe, <0.0001% Ni, and <0.0020% Si.

TABLE A-29. LOW-TEMPERATURE TENSILE PROPERTIES OF A W-15Mo UNIVERSAL FORGING[(a)(6)]

Temperature, F	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation, per cent	Reduction in Area, per cent
285	103.8	90.46	9.5	16.1
435	98.86	86.26	8.9	34.4
530	91.25	78.57	6.5	30.9

(a) Test rate 0.02 inch per minute crosshead speed.

TABLE A-30. HIGH-TEMPERATURE TENSILE PROPERTIES OF A W-15Mo UNIVERSAL FORGING(a)(6)

Specimen Location	Temperature, F	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation, per cent	Reduction in Area, per cent
Web	3000	38.021	36.813	22.8	55
Thick edge	3000	43.718	42.964	20.7	68
As extruded	3000	36.0	34.5	27.8	78
Web	3500	11.403	8.771	68.3	71
Thick edge	3500	10.496	7.920	98.6	92.5
As extruded	3500	11.190	8.060	85	95

(a) Test rate 0.02 inch per minute crosshead speed.

TABLE A-31. AVERAGE TENSILE PROPERTIES OF W-15Mo AT DIFFERENT TEMPERATURES, HOLDING TIMES, AND STRAIN RATES(a)(2)

Temperature, F	Time at Temperature, Prior to Loading, sec	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation in 2 In., per cent	Loading Time to Fracture, sec
75	--	41.1	--	0	13.8
1000	10	31.0	21.1	0.8	15.8
2000	10	29.6	18.2	13.8	20.5
3000	10	24.7	21.5	16.8	22.0
4000	10	7.05	4.7	20.5	22.8
1000	30	25.9	23.6	0.5	0.7
2000	30	32.8	18.5	16.0	1.0
3000	30	32.6	25.3	18.5	1.1
4000	30	14.7	12.1	22.0	1.3

(a) Specimens heated to test temperature within 20 seconds. Two nominal strain rates were used; 0.0005 inch per inch per second, estimated to cause fracture in 20 seconds, and 0.01 inch per inch per second, estimated to cause fracture in 1 second.

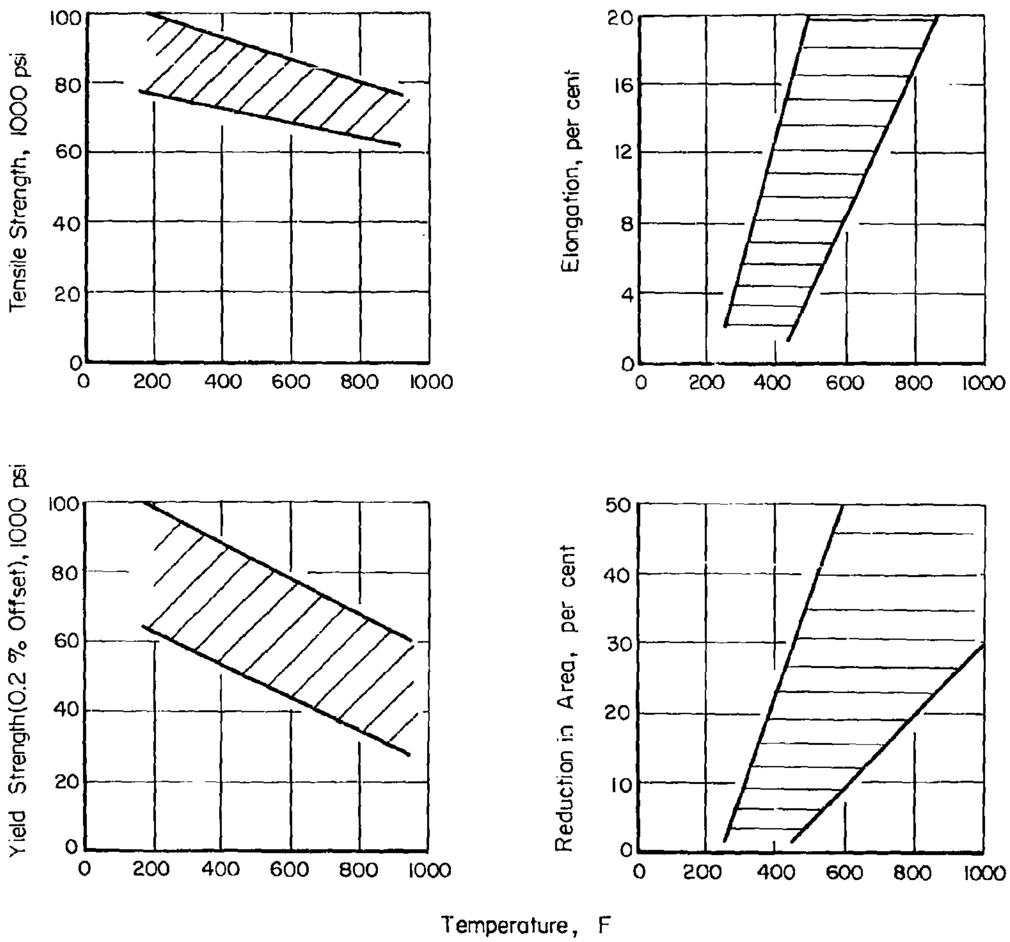


FIGURE A-56. LOW-TEMPERATURE TENSILE PROPERTIES OF ARC-CAST AND EXTRUDED W-15Mo[5]

Test rate 0.02 inch per minute crosshead speed. Data for four extrusions.

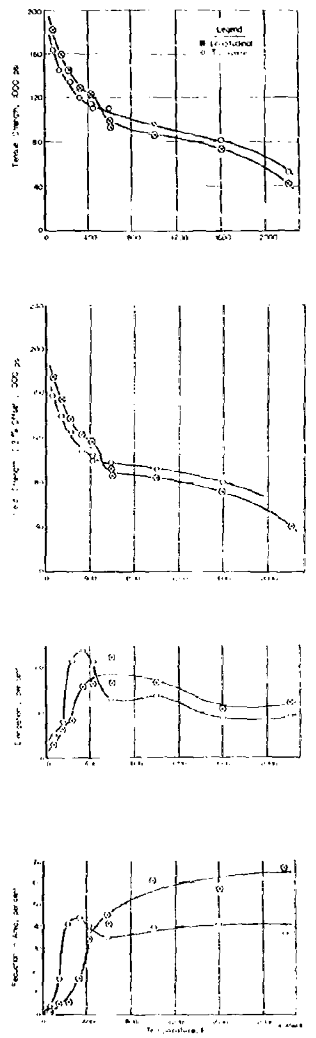


FIGURE A-57. LONGITUDINAL AND TRANSVERSE TENSILE PROPERTIES OF HIGHLY WORKED (WEB) SECTION OF W-15Mo UNIVERSAL FORGINGS (0.105-INCH ROUND)[4]

Test rate 0.02 inch per minute crosshead speed.

Longitudinal and transverse relate to grain orientation of original extruded forging bar; forging direction perpendicular to extrusion direction.

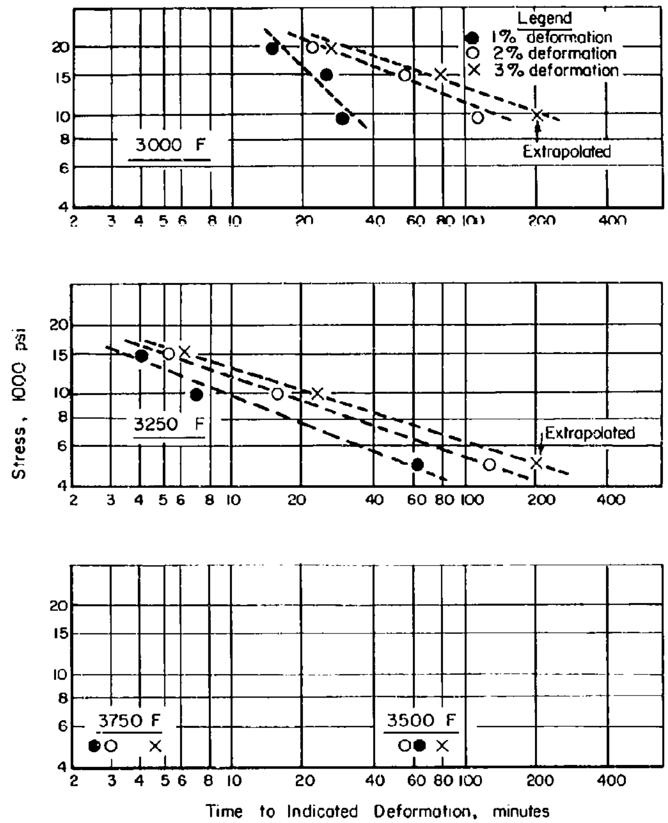


FIGURE A-58. CREEP PROPERTIES OF W-15Mo UNIVERSAL FORGINGS[4]

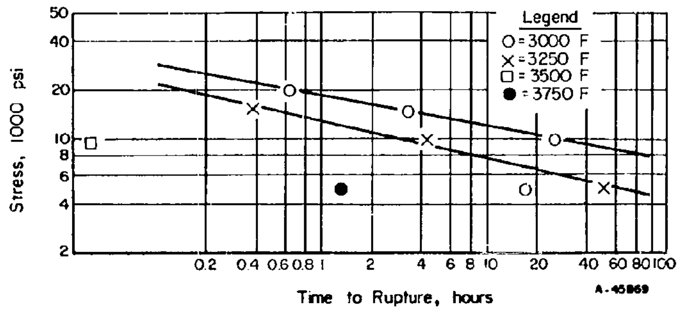


FIGURE A-59. STRESS RUPTURE PROPERTIES OF W-15Mo UNIVERSAL FORGINGS[4]

4. Metallurgical Properties

a. Fabricability: arc-cast and powder-metallurgy billets can be successfully extruded at 3680 F; subsequent forging to complex structural shapes can be accomplished at significantly lower temperatures using conventional die steels and heating and forging equipment[6]; centrifugal cast (graphite mold) rings can be rolled directly to sheet at about 1830 F[3]

b. Transition temperature:

For as-extruded material tested at 0.020 inch per minute crosshead speed (0.160-inch rod)[7]

Method of Consolidation	Transition Temperature, F
Arc	480-590
Powder	450-590
Corefined powder	300

Figure A-60

c. Stress-relief temperature: ~1 hour at 2600 F for arc-melted and extruded (6:1) material[5]

d. Recrystallization temperature: Figure A-61

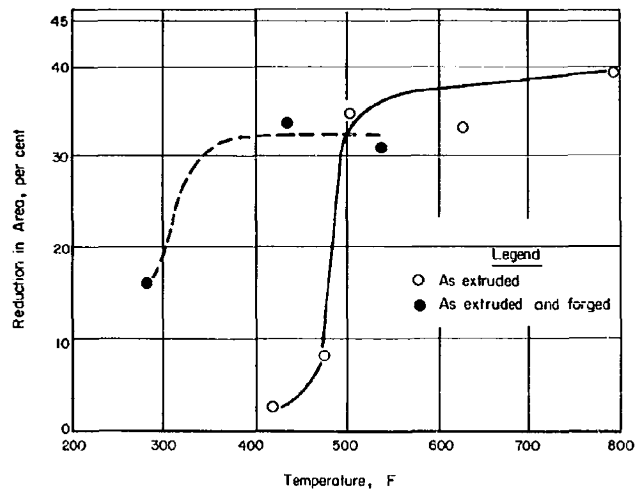


FIGURE A-60. EFFECT OF COLD WORK ON THE TRANSITION TEMPERATURE OF W-15Mo[6]

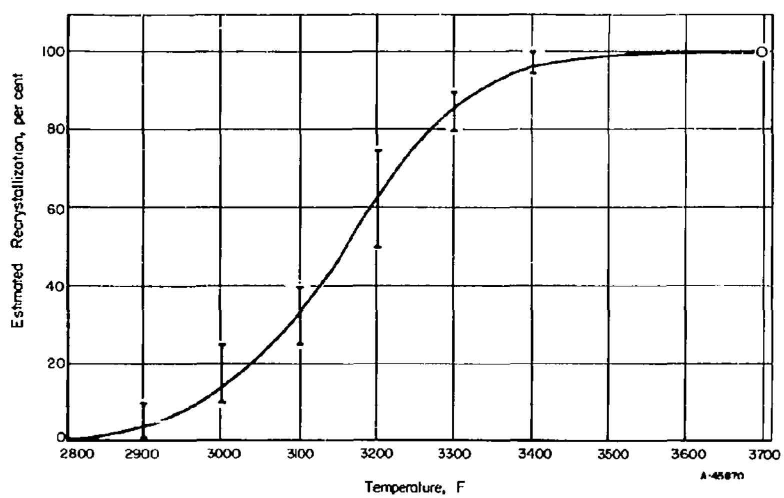


FIGURE A-61. ONE HOUR RECRYSTALLIZATION CURVE FOR ARC-MELTED W-15Mo EXTRUDED AT A 6:1 RATIO AT 3680 F[5]

References

(1) Private Communication from Oregon Metallurgical Corporation (February, 1961).

(2) Kattus, J. R., and Wilhelm, C. C., "The Flexure and Tensile Properties of 85W-15Mo Alloy", Southern Research Institute, Report 4712-1231-I (December 9, 1960).

(3) Barth, V. D., "Review of Recent Developments in the Technology of Tungsten", Battelle Memorial Institute, DMIC Memorandum 127 (September 22, 1961).

(4) Lake, F. N., "Tungsten Forging Development Program", Thompson Ramo Wooldridge, Inc., Contract No. AF 33(600)-41629, AFSC Interim Report 7-797 (V) (November, 1961).

(5) "Tungsten Forging Development Program", Thompson Ramo Wooldridge, Inc., Contract No. AF 33(600)-41629, AMC Interim Report 7-797 (II) (December, 1960).

(6) Lake, F. N., Breznyak, E. J., and Doble, G. S., "Tungsten Forging Development Program", Thompson Ramo Wooldridge, Inc., Contract No. AF 33(600)-41629, AFSC Interim Report 7-797 (IV) (May, 1961).

(7) Lake, F. N., and Breznyak, E. J., "Tungsten Forging Development Program", Thompson Ramo Wooldridge, Inc., Contract No. AF 33(600)-41629, AMC Interim Report 7-797 (III) (March, 1961).

W-3Re

1. Identification of Material

   a. Designation: 3D (General Electric)

   b. Chemical composition: W-3Re

   c. Forms available: wire[1]

2. Physical Properties

   a. Melting point: ~6120F[2]

   b. Density: 0.699 lb/in.^{3} (calculated)

   c. Electrical resistivity: Figure A-62

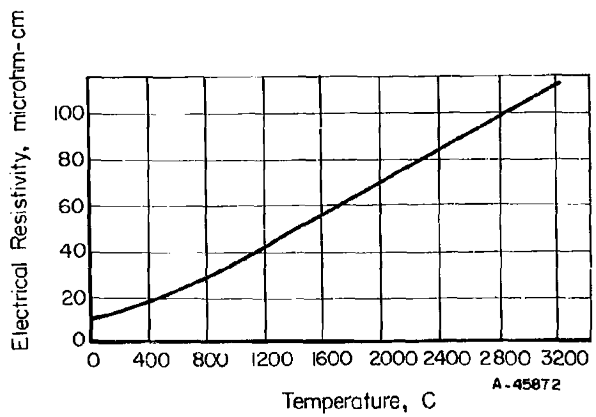


FIGURE A-62. ELECTRICAL RESISTIVITY OF 3D WIRE[1]

3. Mechanical Properties

a. Tensile Properties at Room Temperature

Ultimate tensile strength: Table A-30

Tensile yield strength: Table A-30

Elongation: Table A-30
Figure A-63

b. Effect of Temperature on Tensile Properties

Ultimate tensile strength: Figure A-64

c. Other Selected Mechanical Properties

Hardness: for 3D wire (8 mil)[3]

	3-Minute Annealing Temperature, C					
	1750	2000	2240	2500	2750	2850
RT Hardness, DPH	465	464	414	410	407	377

TABLE A-30. TENSILE PROPERTIES OF 3D WIRE (8 MIL) AT ROOM TEMPERATURE(a)(3)

Property	As Drawn	3-Minute Annealing Temperature, C						
		1750	2000	2240	2500	2750	2850	3000
Tensile Strength, 1000 psi	460	266	240	221	212	206	203	167
Yield Strength, 1000 psi	390	260	238	219	207	187	155	140
Elongation, per cent	1.8	9.2	18	20	23	25.7	27.6	9

(a) Test rate 0.1 inch per inch per minute.

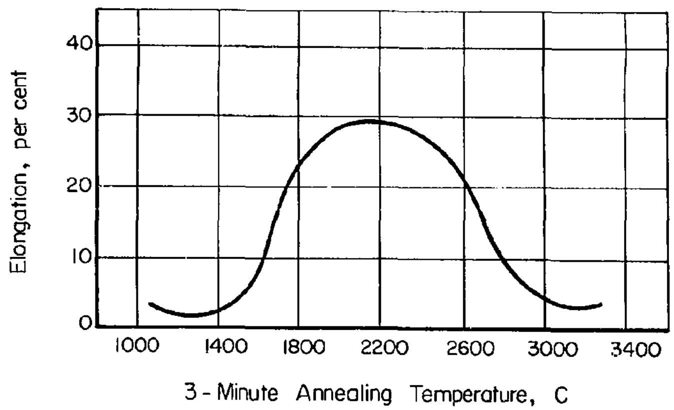


FIGURE A-63. EFFECT OF ANNEALING TEMPERATURE ON THE ROOM-TEMPERATURE DUCTILITY OF 3D WIRE (7 MIL)[1]

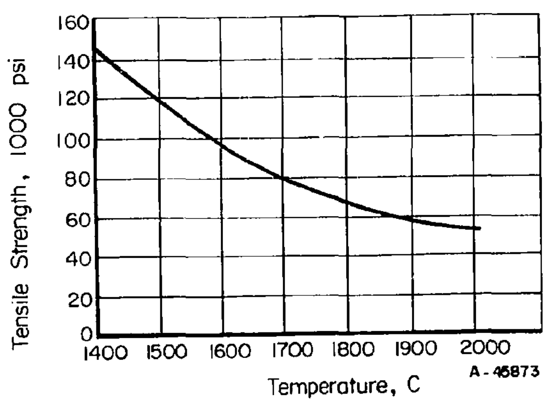


FIGURE A-64. EFFECT OF TEMPERATURE ON THE TENSILE STRENGTH OF 3D WIRE (8 MIL)[1]

Test rate 0.4 inch per inch per minute.

4. Metallurgical Properties

a. Fabricability: sintered ingots can be swaged to rod followed by wire drawing using conventional practice; as reduction proceeds, working temperatures are dropped from 2910 F for initial swaging to 1560 F for the final drawing pass providing warm-cold work exceeding 99 per cent reduction in area[3]

b. Transition temperature: highly worked or annealed wire has useful room-temperature ductility[3]

c. Stress-relief temperature: 3 minutes at 4060 F for as-heavily-drawn wire[3]

d. Recrystallization temperature: 3 minutes at 5430 F for as-heavily-drawn wire[3]

References

(1) "Tungsten-Rhenium Alloy Wire", General Electric Co., Product Data Sheet 1300-C (January 22, 1962).

(2) English, J. J., "Binary and Ternary Phase Diagrams of Columbium, Molybdenum, Tantalum, and Tungsten", Battelle Memorial Institute, DMIC Report 152 (April 28, 1961).

(3) Pugh, J. W., Amra, L. H., and Hurd, D. T., "Properties of Tungsten-Rhenium Lamp Wire", Trans. ASM, 55 (3) (September, 1962).

W-5Re

1. Identification of Material

   a. Chemical composition: W-5Re

   b. Forms available: wire[1]

2. Physical Properties

   a. Melting point: 6060 F[1]

   b. Density: 0.701 lb/in.^{3}

   c. Electrical resistivity: 12.7 microhm-cm for 8 mil wire[2]

Figure A-65

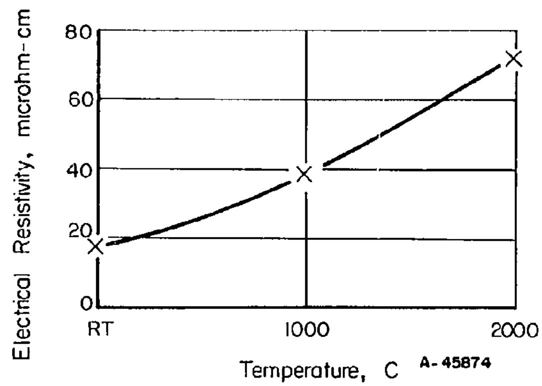


FIGURE A-65. ELECTRICAL RESISTIVITY OF W-5Re WIRE[1]

3. Mechanical Properties

a. Tensile Properties at Room Temperature

Ultimate tensile strength: Table A-31

Tensile yield strength: Table A-31

Elongation: Table A-31

b. Effect of Temperature on Tensile Properties

Ultimate tensile strength: Figures A-66 and A-67

Elongation: Figure A-66

c. Other Selected Mechanical Properties

Hardness: for 8-mil wire[2]

	3-Minute Annealing Temperature, C		
	2000	2750	2850
RT Hardness, DPH	503	424	389

TABLE A-32. TENSILE PROPERTIES OF W-5Re WIRE (8 MIL) AT ROOM TEMPERATURE[a](2)

Property	As Drawn	3-Minute Annealing Temperature, C						
		1750	2000	2240	2500	2750	2850	3000
Tensile Strength, 1000 psi	481	280	245	233	225	217	220	182
Yield Strength, 1000 psi	390	271	241	230	215	188	147	137
Elongation, per cent	1.6	5.1	16.3	19.3	18.0	16.0	23.9	11.5

(a) Test rate 0.1 inch per inch per minute.

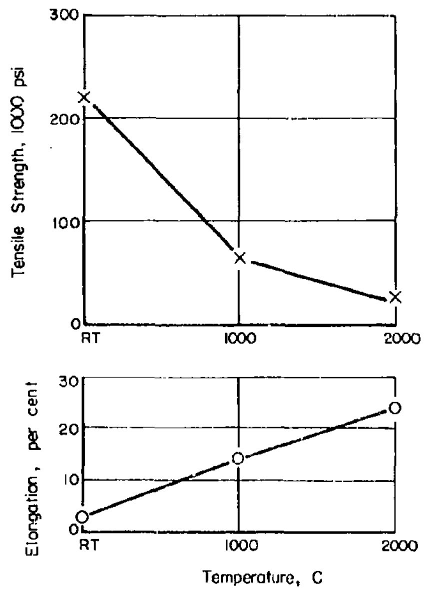


FIGURE A-66. EFFECT OF TEMPERATURE ON THE STRENGTH AND DUCTILITY OF RECRYSTALLIZED W-5Re WIRE[1]

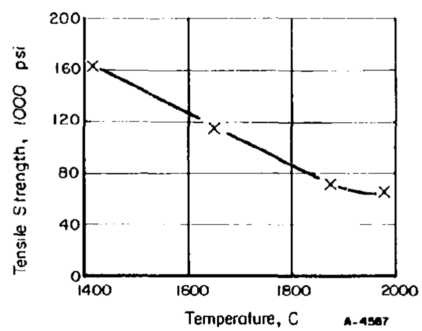


FIGURE A-67. EFFECT OF TEMPERATURE ON THE TENSILE STRENGTH OF W-5Re WIRE (8 MIL)[2]

Test rate 0.4 inch per inch per minute.

4. Metallurgical Properties

a. Fabricability: sintered ingots can be swaged to rod followed by wire drawing using conventional practice; as reduction proceeds working temperatures are dropped from 2910 F for initial swaging to 1560 F for the final drawing pass providing warm-cold work exceeding 99 per cent reduction in area[2]

b. Transition temperature: highly worked or annealed wire has useful room-temperature ductility[2]

c. Stress-relief temperature: 3 minutes at 4060 F for as-heavily-drawn wire[2]

d. Recrystallization temperature: 3 minutes at 5430 F for as-heavily-drawn wire[2]

A-121 and A-122

References

(1) "Tungsten-Rhenium Thermocouple Alloys", Technical Brochure, Hoskins Manufacturing Co.

(2) Pugh, J. W., Amra, L. H., and Hurd, D. T., "Properties of Tungsten-Rhenium Lamp Wire", Trans. ASM, 55 (3) (September, 1962).

1. Identification of Material

   a. Chemical composition: W-26Re

   b. Forms available: tubing and wire[1,2]

2. Physical Properties

   a. Melting point: 5650 F[1]

   b. Density: 0.714 lb/in.^{3}

   c. Electrical resistivity: Figure A-68

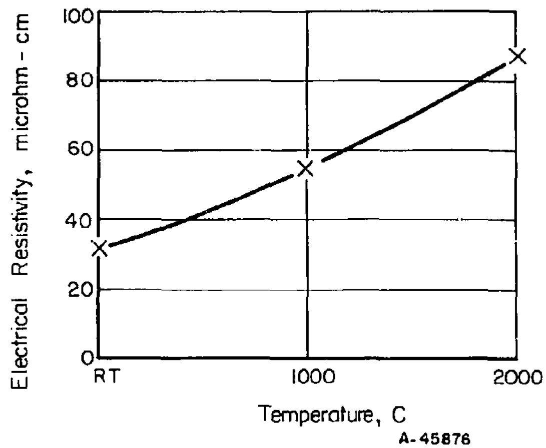


FIGURE A-68. ELECTRICAL RESISTIVITY OF W-26Re WIRE[1]

3. Mechanical Properties

a. Tensile Properties at Room Temperature

Ultimate tensile strength: for wire[1]

	Wrought	Recrystallized
1000 PSI	305	200

Elongation: for wire[1]

	Wrought	Recrystallized
Per Cent	7	11

b. Effect of Temperature on Tensile Properties

Ultimate tensile strength: Figure D-11-2

Elongation: Figure A-69

c. Other Selected Mechanical Properties

Bend ductility: for 15 mil wire[3]

	Wrought	Recrystallized
RT Bend Radius, T	1	1

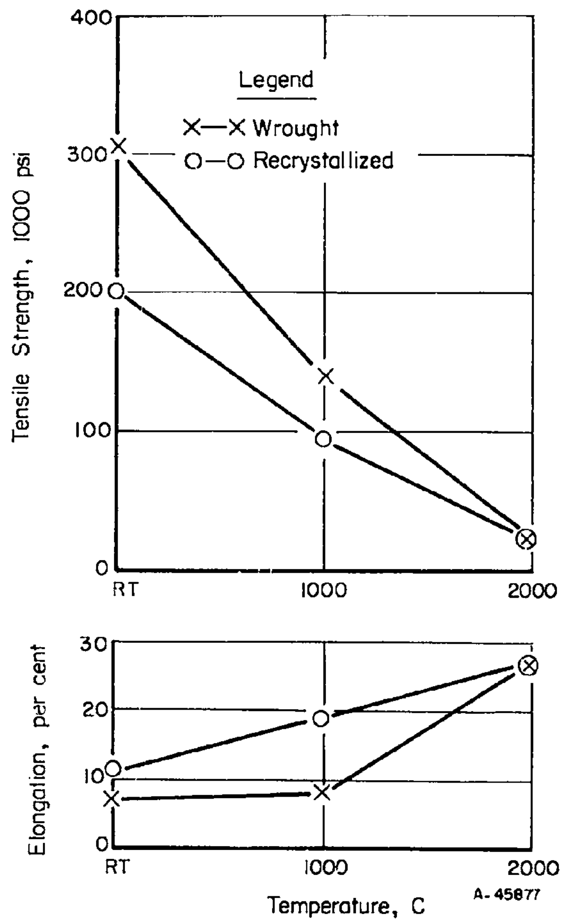


FIGURE A-69. EFFECT OF TEMPERATURE ON THE STRENGTH AND DUCTILITY OF W-26Re WIRE[1]

4. Metallurgical Properties

a. Fabricability: laboratory-produced arc-cast ingots can be forged at 2730 F; flat and rod rolling can be conducted as low as 1650 F[3]

b. Transition temperature:

	Wrought[2]	Recrystallized[2]
Temperature, F	-200	-100

c. Recrystallization temperature: hardening effects of cold working are retained to approximately 1000 F higher than unalloyed tungsten[2]

References

(1) "Tungsten-Rhenium Thermocouple Alloys", Technical Brochure, Hoskins Manufacturing Co.

(2) "Tungsten-26% Rhenium Seamless Tubing", Technical Brochure, Hoskins Manufacturing Co.

(3) Gonser, B. W., Rhenium, Elsevier Publishing Co., New York (1962), pp 110-125.

LIST OF DMIC TECHNICAL REPORTS ISSUED
DEFENSE METALS INFORMATION CENTER

Battelle Memorial Institute

Columbus 1, Ohio

Copies of the technical reports listed below may be obtained from DMIC at no cost by Government agencies, and by Government contractors, subcontractors, and their suppliers. Others may obtain copies from the Office of Technical Services, Department of Commerce, Washington 25, D. C. See PB numbers and prices in parentheses.

DMIC Report Number	Title
46D	Department of Defense Titanium Sheet-Rolling Program – Uniform Testing Procedure for Sheet Materials, September 12, 1958 (PB 121649 $1.25)
46E	Department of Defense Titanium Sheet-Rolling Program – Thermal Stability of the Titanium Sheet-Rolling-Program Alloys, November 25, 1958 (PB 151061 $1.25)
46F	Department of Defense Titanium Sheet-Rolling Program Status Report No. 4, March 20, 1959 (PB 151065 $2.25)
46G	Department of Defense Titanium Sheet-Rolling Program – Time-Temperature-Transformation Diagrams of the Titanium Sheet-Rolling Program Alloys, October 19, 1959 (PB 151075 $2.25)
46H	Department of Defense Titanium Sheet-Rolling Program, Status Report No. 5, June 1, 1960 (PB 151087 $2.00)
46I	Statistical Analysis of Tensile Properties of Heat-Treated Ti-4Al-3Mo-1V Sheet, September 16, 1960 (PB 151095 $1.25)
46J	Statistical Analysis of Tensile Properties of Heat-Treated Ti-4Al-3Mo-1V and Ti-2.5Al-16V Sheet, June 6, 1961 (AD 259284 $1.25)
106	Beryllium for Structural Applications, August 15, 1958 (PB 121648 $3.00)
107	Tensile Properties of Titanium Alloys at Low Temperature, January 15, 1959 (PB 151062 $1.25)
108	Welding and Brazing of Molybdenum, March 1, 1959 (PB 151063 $1.25)
109	Coatings for Protecting Molybdenum From Oxidation at Elevated Temperature, March 6, 1959 (PB 151064 $1.25)
110	The All-Beta Titanium Alloy (Ti-13V-11Cr-3Al), April 17, 1959 (PB 151066 $3.00)
111	The Physical Metallurgy of Precipitation-Hardenable Stainless Steels, April 20, 1959 (PB 151067 $2.00)
112	Physical and Mechanical Properties of Nine Commercial Precipitation-Hardenable Stainless Steels, May 1, 1959 (PB 151068 $3.25)
113	Properties of Certain Cold-Rolled Austenitic Stainless Sheet Steels, May 15, 1959 (PB 151069 $1.75)
114	Ductile-Brittle Transition in the Refractory Metals, June 25, 1959 (PB 151070 $2.00)
115	The Fabrication of Tungsten, August 14, 1959 (PB 151071 $1.75)
116R	Design Information on 5Cr-Mo-V Alloy Steels (H-11 and 5Cr-Mo-V Aircraft Steel) for Aircraft and Missiles (Revised), September 30, 1960 (PB 151072-R $1.50)
117	Titanium Alloys for High-Temperature Use Strengthened by Fibers or Dispersed Particles, August 31, 1959 (PB 151073 $2.00)
118	Welding of High-Strength Steels for Aircraft and Missile Applications, October 12, 1959 (PB 151074 $2.25)
119	Heat Treatment of High-Strength Steels for Aircraft Applications, November 27, 1959 (PB 151076 $2.50)
120	A Review of Certain Ferrous Castings Applications in Aircraft and Missiles, December 18, 1959 (PB 151077 $1.50)
121	Methods for Conducting Short-Time Tensile, Creep, and Creep-Rupture Tests Under Conditions of Rapid Heating, December 20, 1959 (PB 151078 $1.25)
122	The Welding of Titanium and Titanium Alloys, December 31, 1959 (PB 151079 $1.75)
123	Oxidation Behavior and Protective Coatings for Columbium and Columbium-Base Alloys, January 15, 1960 (PB 151080 $2.25)
124	Current Tests for Evaluating Fracture Toughness of Sheet Metals at High Strength Levels, January 28, 1960 (PB 151081 $2.00)
125	Physical and Mechanical Properties of Columbium and Columbium-Base Alloys, February 22, 1960 (PB 151082 $1.75)
126	Structural Damage in Thermally Cycled René 41 and Astroloy Sheet Materials, February 29, 1960 (PB 151083 $0.75)
127	Physical and Mechanical Properties of Tungsten and Tungsten-Base Alloys, March 15, 1960 (PB 151084 $1.75)
128	A Summary of Comparative Properties of Air-Melted and Vacuum-Melted Steels and Superalloys, March 28, 1960 (PB 151085 $2.75)
129	Physical Properties of Some Nickel-Base Alloys, May 20, 1960 (PB 151086 $2.75)
130	Selected Short-Time Tensile and Creep Data Obtained Under Conditions of Rapid Heating, June 17, 1960 (PB 151088 $2.25)
131	New Developments of the Welding of Metals, June 24, 1960 (PB 151089 $1.25)
132	Design Information on Nickel-Base Alloys for Aircraft and Missiles, July 20, 1960 (PB 151090 $3.00)
133	Tantalum and Tantalum Alloys, July 25, 1960 (PB 151091 $5.00)
134	Strain Aging of Refractory Metals, August 12, 1960 (PB 151092 $1.75)
135	Design Information on PH 15-7 Mo Stainless Steel for Aircraft and Missiles, August 22, 1960 (PB 151093 $1.25)

DMIC Report Number	Title
136A	The Effects of Alloying Elements in Titanium, Volume A. Constitution, September 15, 1960 (PB 151094 $3.50)
136B	The Effects of Alloying Elements in Titanium, Volume B. Physical and Chemical Properties, Deformation and Transformation Characteristics, May 29, 1961 (AD 260226 $3.00)
137	Design Information on 17-7 PH Stainless Steels for Aircraft and Missiles, September 23, 1960 (PB 151096 $1.00)
138	Availability and Mechanical Properties of High-Strength Steel Extrusions, October 26, 1960 (PB 151097 $1.75)
139	Melting and Casting of the Refractory Metals Molybdenum, Columbium, Tantalum, and Tungsten, November 18, 1960 (PB 151098 $1.00)
140	Physical and Mechanical Properties of Commercial Molybdenum-Base Alloys, November 30, 1960 (PB 151099 $3.00)
141	Titanium-Alloy Forgings, December 19, 1960 (PB 151100 $2.25)
142	Environmental Factors Influencing Metals Applications in Space Vehicles, December 27, 1960 (PB 151101 $1.25)
143	High-Strength-Steel Forgings, January 5, 1961 (PB 151102 $1.75)
144	Stress-Corrosion Cracking – A Nontechnical Introduction to the Problem, January 6, 1961 (PB 151103 $0.75)
145	Design Information on Titanium Alloys for Aircraft and Missiles, January 10, 1961 (PB 151104 $2.25)
146	Manual for Beryllium Prospectors, January 18, 1961 (PB 151105 $1.00)
147	The Factors Influencing the Fracture Characteristics of High-Strength Steel, February 6, 1961 (PB 151106 $1.25)
148	Review of Current Data on the Tensile Properties of Metals at Very Low Temperatures, February 14, 1961 (PB 151107 $2.00)
149	Brazing for High Temperature Service, February 21, 1961 (PB 151108 $1.00)
150	A Review of Bending Methods for Stainless Steel Tubing, March 2, 1961 (PB 151109 $1.50)
151	Environmental and Metallurgical Factors of Stress-Corrosion Cracking in High-Strength Steels, April 14, 1961 (PB 151110 $0.75)
152	Binary and Ternary Phase Diagrams of Columbium, Molybdenum, Tantalum, and Tungsten, April 28, 1961 (AD 257739 $3.50)
153	Physical Metallurgy of Nickel-Base Superalloys, May 5, 1961 (AD 258041 $1.25)
154	Evolution of Ultrahigh-Strength, Hardenable Steels for Solid-Propellant Rocket-Motor Cases, May 25, 1961 (AD 257976 $1.25)
155	Oxidation of Tungsten, July 17, 1961 (AD 263598 $3.00)
156	Design Information on AM-350 Stainless Steel for Aircraft and Missiles, July 28, 1961 (AD 262407 $1.50)
157	A Summary of the Theory of Fracture in Metals, August 7, 1961 (PB 181081 $1.75)
158	Stress-Corrosion Cracking of High-Strength Stainless Steels in Atmospheric Environments, September 15, 1961 (AD 266005 $1.25)
159	Gas-Pressure Bonding, September 25, 1961 (AD 265133 $1.25)
160	Introduction to Metals for Elevated-Temperature Use, October 27, 1961 (AD 268647 $2.50)
161	Status Report No. 1 on Department of Defense Refractory Metals Sheet-Rolling Program, November 2, 1961 (AD 267077 $1.00)
162	Coatings for the Protection of Refractory Metals From Oxidation, November 24, 1961 (AD 271384 $3.50)
163	Control of Dimensions in High-Strength Heat-Treated Steel Parts, November 29, 1961 (AD 270045 $1.00)
164	Semiaustenitic Precipitation-Hardenable Stainless Steels, December 6, 1961 (AD 274805 $2.75)
165	Methods of Evaluating Welded Joints, December 28, 1961 (AD 272088 $2.25)
166	The Effect of Nuclear Radiation on Structural Metals, September 15, 1961 (AD 265839 $2.50)
167	Summary of the Fifth Meeting of the Refractory Composites Working Group, March 12, 1962 (AD 274804 $2.00)
168	Beryllium for Structural Applications, 1958-1960, May 18, 1962 (AD 278723 $3.50)
169	The Effect of Molten Alkali Metals on Containment Metals and Alloys at High Temperatures, May 18, 1962 (AD 282932 $1.50)
170	Chemical Vapor Deposition, June 4, 1962 (AD 281887 $2.25)
171	The Physical Metallurgy of Cobalt-Base Superalloys, July 6, 1962 (AD 283356 $2.25)
172	Background for the Development of Materials To Be Used in High-Strength-Steel Structural Weldments, July 31, 1962 (AD 284265 $3.00)
173	New Developments in Welded Fabrication of Large Solid-Fuel Rocket-Motor Cases, August 6, 1962 (AD 284829 $1.00)
174	Electron-Beam Processes, September 15, 1962 (AD 287433 $1.75)
175	Summary of the Sixth Meeting of the Refractory Composites Working Group, September 24, 1962 (AD 287029 $1.75)
176	Status Report No. 2 on Department of Defense Refractory Metals Sheet-Rolling Program, October 15, 1962 (AD 288127 $1.25)
177	Thermal Radiative Properties of Selected Materials, November 15, 1962, Vol. I (AD 294345 $3.00)
177	Thermal Radiative Properties of Selected Materials, November 15, 1962, Vol. II (AD 294346 $4.00)
178	Steels for Large Solid-Propellant Rocket-Motor Cases, November 20, 1962
179	A Guide to the Literature on High-Velocity Metalworking, December 3, 1962
180	Design Considerations in Selecting Materials for Large Solid-Propellant Rocket-Motor Cases, December 10, 1962
181	Joining of Nickel-Base Alloys, December 20, 1962
182	Structural Considerations in Developing Refractory Metal Alloys, January 31, 1963
183	Binary and Ternary Phase Diagrams of Columbium, Molybdenum, Tantalum, and Tungsten (Supplement to DMIC Report 152), February 7, 1963
184	Summary of the Seventh Meeting of the Refractory Composites Working Group, May 30, 1963
185	The Status and Properties of Titanium Alloys for Thick Plate, June 14, 1963
186	The Effect of Fabrication History and Microstructure on the Mechanical Properties of Refractory Metals and Alloys, July 10, 1963
187	The Application of Ultrasonic Energy in the Deformation of Metals, August 16, 1963

DMIC Report Number	Title
188	The Engineering Properties of Columbium and Columbium Alloys, September 6, 1963
189	The Engineering Properties of Tantalum and Tantalum Alloys, September 13, 1963
190	The Engineering Properties of Molybdenum and Molybdenum Alloys, September 20, 1963

Battelle Memorial Institute, Defense Metals Information Center, Columbus, Ohio, THE ENGINEERING PROPERTIES OF TUNGSTEN AND TUNGSTEN ALLOYS, by F. F. Schmidt and H. R. Ogden. September 27, 1963. [133] pp incl. illus., tables, refs. DMIC Report 191.
[AF 33(616)-7747]

Unclassified report

This report presents the results of a state-of-the-art survey covering tungsten and ten of its alloys. All data are given in tabular and graphical form covering some of the more important physical, mechanical, and metallurgical properties for each material. References are given at the conclusion of each material section.

UNCLASSIFIED

1. Tungsten
2. Physical Properties
3. Mechanical Properties
4. Metallurgical Properties

I. Battelle Memorial Institute
II. Defense Metals Information Center
III. Contract AF33(616)-7747

Battelle Memorial Institute, Defense Metals Information Center, Columbus, Ohio, THE ENGINEERING PROPERTIES OF TUNGSTEN AND TUNGSTEN ALLOYS, by F. F. Schmidt and H. R. Ogden. September 27, 1963. [133] pp incl. illus., tables, refs. DMIC Report 191.
[AF 33(616)-7747]

Unclassified report

This report presents the results of a state-of-the-art survey covering tungsten and ten of its alloys. All data are given in tabular and graphical form covering some of the more important physical, mechanical, and metallurgical properties for each material. References are given at the conclusion of each material section.

UNCLASSIFIED

1. Tungsten
2. Physical Properties
3. Mechanical Properties
4. Metallurgical Properties

I. Battelle Memorial Institute
II. Defense Metals Information Center
III. Contract AF33(616)-7747

Battelle Memorial Institute, Defense Metals Information Center, Columbus, Ohio, THE ENGINEERING PROPERTIES OF TUNGSTEN AND TUNGSTEN ALLOYS, by F. F. Schmidt and H. R. Ogden. September 27, 1963. [133] pp incl. illus., tables, refs. DMIC Report 191.
[AF 33(616)-7747]

Unclassified report

This report presents the results of a state-of-the-art survey covering tungsten and ten of its alloys. All data are given in tabular and graphical form covering some of the more important physical, mechanical, and metallurgical properties for each material. References are given at the conclusion of each material section.

UNCLASSIFIED

1. Tungsten
2. Physical Properties
3. Mechanical Properties
4. Metallurgical Properties

I. Battelle Memorial Institute
II. Defense Metals Information Center
III. Contract AF33(616)-7747

Battelle Memorial Institute, Defense Metals Information Center, Columbus, Ohio, THE ENGINEERING PROPERTIES OF TUNGSTEN AND TUNGSTEN ALLOYS, by F. F. Schmidt and H. R. Ogden. September 27, 1963. [133] pp incl. illus., tables, refs. DMIC Report 191.
[AF 33(616)-7747]

Unclassified report

This report presents the results of a state-of-the-art survey covering tungsten and ten of its alloys. All data are given in tabular and graphical form covering some of the more important physical, mechanical, and metallurgical properties for each material. References are given at the conclusion of each material section.

UNCLASSIFIED

1. Tungsten
2. Physical Properties
3. Mechanical Properties
4. Metallurgical Properties

I. Battelle Memorial Institute
II. Defense Metals Information Center
III. Contract AF33(616)-7747

Battelle Memorial Institute, Defense Metals Information Center, Columbus, Ohio, THE ENGINEERING PROPERTIES OF TUNGSTEN AND TUNGSTEN ALLOYS, by F. F. Schmidt and H. R. Ogden. September 27, 1963. [133] pp incl. illus., tables, refs. DMIC Report 191.
[AF 33(616)-7747]

Unclassified report

This report presents the results of a state-of-the-art survey covering tungsten and ten of its alloys. All data are given in tabular and graphical form covering some of the more important physical, mechanical, and metallurgical properties for each material. References are given at the conclusion of each material section.

UNCLASSIFIED

1. Tungsten
2. Physical Properties
3. Mechanical Properties
4. Metallurgical Properties

I. Battelle Memorial Institute
II. Defense Metals Information Center
III. Contract AF33(616)-7747

Battelle Memorial Institute, Defense Metals Information Center, Columbus, Ohio, THE ENGINEERING PROPERTIES OF TUNGSTEN AND TUNGSTEN ALLOYS, by F. F. Schmidt and H. R. Ogden. September 27, 1963. [133] pp incl. illus., tables, refs. DMIC Report 191.
[AF 33(616)-7747]

Unclassified report

This report presents the results of a state-of-the-art survey covering tungsten and ten of its alloys. All data are given in tabular and graphical form covering some of the more important physical, mechanical, and metallurgical properties for each material. References are given at the conclusion of each material section.

UNCLASSIFIED

1. Tungsten
2. Physical Properties
3. Mechanical Properties
4. Metallurgical Properties

I. Battelle Memorial Institute
II. Defense Metals Information Center
III. Contract AF33(616)-7747

Battelle Memorial Institute, Defense Metals Information Center, Columbus, Ohio, THE ENGINEERING PROPERTIES OF TUNGSTEN AND TUNGSTEN ALLOYS, by F. F. Schmidt and H. R. Ogden. September 27, 1963. [133] pp incl. illus., tables, refs. DMIC Report 191.
[AF 33(616)-7747]

Unclassified report

This report presents the results of a state-of-the-art survey covering tungsten and ten of its alloys. All data are given in tabular and graphical form covering some of the more important physical, mechanical, and metallurgical properties for each material. References are given at the conclusion of each material section.

UNCLASSIFIED

1. Tungsten
2. Physical Properties
3. Mechanical Properties
4. Metallurgical Properties

I. Battelle Memorial Institute
II. Defense Metals Information Center
III. Contract AF33(616)-7747

Battelle Memorial Institute, Defense Metals Information Center, Columbus, Ohio, THE ENGINEERING PROPERTIES OF TUNGSTEN AND TUNGSTEN ALLOYS, by F. F. Schmidt and H. R. Ogden. September 27, 1963. [133] pp incl. illus., tables, refs. DMIC Report 191.
[AF 33(616)-7747]

Unclassified report

This report presents the results of a state-of-the-art survey covering tungsten and ten of its alloys. All data are given in tabular and graphical form covering some of the more important physical, mechanical, and metallurgical properties for each material. References are given at the conclusion of each material section.

UNCLASSIFIED

1. Tungsten
2. Physical Properties
3. Mechanical Properties
4. Metallurgical Properties

I. Battelle Memorial Institute
II. Defense Metals Information Center
III. Contract AF33(616)-7747

UNCLASSIFIED

UNCLASSIFIED