UNCLASSIFIED

AD 426264

DEFENSE DOCUMENTATION CENTER

FOR

SCIENTIFIC AND TECHNICAL INFORMATION

CAMERON STATION, ALEXANDRIA VIRGINIA

UNCLASSIFIED

NOTICE: When government or other drawings, specifications or other data are used for any purpose other than in connection with a definitely related government procurement operation, the U. S. Government thereby incurs no responsibility, nor any obligation whatsoever; and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use or sell any patented invention that may in any way be related thereto.

426264

DMIC Report 190
Sep[illegible]r 20, 1963

THE ENGINEERING PROPERTIES OF MOLYBDENUM AND MOLYBDENUM ALLOYS

426264

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(8-9275)

Best Available Copy

DMIC Report 190
September 20, 1963

THE ENGINEERING PROPERTIES OF MOLYBDENUM AND MOLYBDENUM 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 engineering-property data of these four refractory metals and alloys. This report covers molybdenum and molybdenum 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
R. W. Werner, Lawrence Radiation Laboratory
G. P. Trost, Metals and Controls, Inc.
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

	Page
SUMMARY	1
INTRODUCTION	3
ORGANIZATION OF DATA PRESENTED IN THE APPENDIX	5
APPENDIX	
MOLYBDENUM AND ITS ALLOYS	A-1
Unalloyed Molybdenum	A-1
Mo-1.5Cb	A-75
Mo-0.05Zr	A-91
Mo-0.5Zr	A-105
Mo-0.5Ti	A-119
Mo-0.5Ti-0.08Zr-0.03C	A-183
Mo-1.2Ti-0.25Zr-0.15C	A-237
Mo-25W-0.1Zr-0.03C	A-257
Mo-30W	A-271
Mo-50W	A-277

THE ENGINEERING PROPERTIES OF
MOLYBDENUM AND MOLYBDENUM ALLOYS

SUMMARY

~~This report presents~~ the results of a state-of-the-art survey covering molybdenum and nine of its most promising alloys are presented. 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 molybdenum and nine 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 molybdenum and each of its nine alloys. Properties and alloys covered in this report are listed in Table 1.

Trends in molybdenum-alloy development include new dispersion-strengthened alloys and alloys combining solution and dispersion strengthening, with emphasis on higher elevated-temperature strengths than those exhibited for the more common commercial molybdenum alloys. The area of fabrication is also receiving considerable attention in an attempt to optimize selected properties.

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
Molybdenum		x	x	x		x	x	x	x	x			x	x	x	x	x	x	x	x		x	x	x	x	x
Mo-1.5Cb			x	x			x						x	x	x	x			x	x		x	x		x	x
Mo-0.05Zr			x	x		x	x						x	x	x	x			x	x		x	x	x	x	x
Mo-0.5Zr			x	x		x	x						x	x	x	x		x	x	x		x	x		x	x
Mo-0.5Ti		x	x	x		x	x	x	x				x	x	x	x	x	x	x	x		x	x	x	x	x
Mo-0.5Ti-0.08Zr-0.03C		x	x	x		x	x						x	x	x	x	x	x	x	x		x	x	x	x	x
Mo-1.2Ti 0.25Zr-0.15C		x	x	x			x						x	x	x	x			x	x		x	x		x	x
Mo 25W-0.1Zr-0.03C		x	x	x		x	x						x	x	x	x			x	x		x	x		x	x
Mo-30W			x	x		x	x			x			x	x	x	x	x		x	x		x	x	x	x	x
Mo-50W			x	x		x	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 A

MOLYBDENUM AND ITS ALLOYS

APPENDIX A

MOLYBDENUM AND ITS ALLOYS

Unalloyed Molybdenum

1. Identification of material

   a. Designation: many, depending upon individual supplier

   b. Chemical composition: Tables A-1 and A-2

   c. Forms available: billets, forgings, strip, sheet, foil, plate, bar, rod, and wire[1-4]

TABLE A-1. CHEMICAL REQUIREMENTS FOR MOLYBDENUM PRODUCTS AS PRODUCED BY ARC-CAST AND POWDER-METALLURGY TECHNIQUES[a][1-4]

Element	Content, Maximum, weight per cent	
	Arc Cast	Powder Metallurgy
C	0.010-0.040	0.010
O	0.0030	0.0070
N	0.0010	0.0020
Fe	0.020	0.020
Ni	0.010	0.010
Si	0.010	0.010
Mo	99.90 min	99.90 min

(a) For forgings, billets for reforging, strip, sheet, foil, plate, bar, rod, and wire.

TABLE A-2. REPRESENTATIVE ANALYSES OF MOLYBDENUM AS PRODUCED BY VARIOUS SUPPLIERS

Element	Content, Maximum, weight per cent				
	Arc Cast			Powder Metallurgy, Sylvania[d][11]	Arc Cast or Powder Metallurgy, Westinghouse[e][12]
	Climax[5,6]		Universal Cyclops[c][7-10]		
	(a)	(b)			
Al	--	--	0.002	0.0010	0.0020
C	0.03	0.01-0.04	0.01-0.04	0.0050	0.0050
Ca	--	--	0.002	0.0010	0.0020
Co	--	--	0.002	--	0.0040
Cr	--	--	0.004	0.0050	0.0020
Cu	--	--	0.002	0.0010	0.0020
Fe	0.008	0.010	0.010	0.0050	0.0050
H	0.0005	0.0005	0.001	0.0010	0.0020
K	--	--	0.001	--	--
Pb	--	--	0.002	0.0010	0.0010
Mg	--	--	0.002	0.0010	0.0020
Mn	--	--	0.002	0.0010	0.0010
Mo	99.9 min	99.9 min	99.9 min	--	99.95 min
Na	--	--	0.001	--	--
N	0.002	0.002	0.001	0.0020	0.0020
Ni	0.002	0.002	0.002	0.0050	0.0050
O	0.0015	0.0015	0.002	0.0030	0.0100
Si	0.008	0.008	0.020	0.0050	0.0050
Sn	--	--	0.004	0.0050	0.0050
Ti	--	--	0.002	--	0.0020
W	--	--	0.002	--	0.0040
Zr	--	--	0.002	--	0.0020

(a) For forging billets.
(b) For wrought bars.
(c) For billets, bar, plate, and sheet.
(d) For billets, slabs, and rings.
(e) For sheet, plate, and bar.

2 Physical Properties

a. Melting point: 4730 F[13]

b. Density: 0.369 lb/in.^{3}[13]

c. Thermal expansion: Figure A-1

d. Thermal conductivity: Figure A-2

e. Electrical resistivity: Figures A-3 through A-5

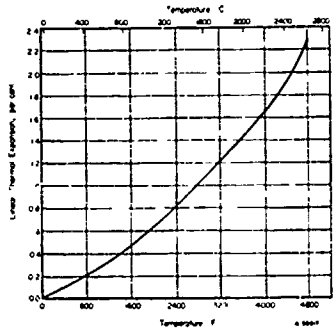


FIGURE A-1. EFFECT OF TEMPERATURE ON THE LINEAR THERMAL EXPANSION OF COMMERCIAL-PURITY MOLYBDENUM[14]

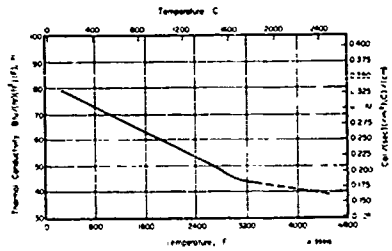


FIGURE A-2. EFFECT OF TEMPERATURE ON THE THERMAL CONDUCTIVITY OF COMMERCIAL-PURITY MOLYBDENUM[14]

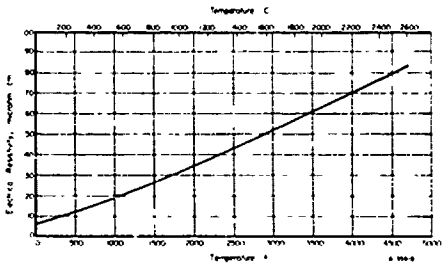


FIGURE A-3. EFFECT OF TEMPERATURE ON THE ELECTRICAL RESISTIVITY OF COMMERCIAL-PURITY MOLYBDENUM[15]

Example:

Resistance per foot of .002-inch-diameter molybdenum at 500 K = 16.7 ohms

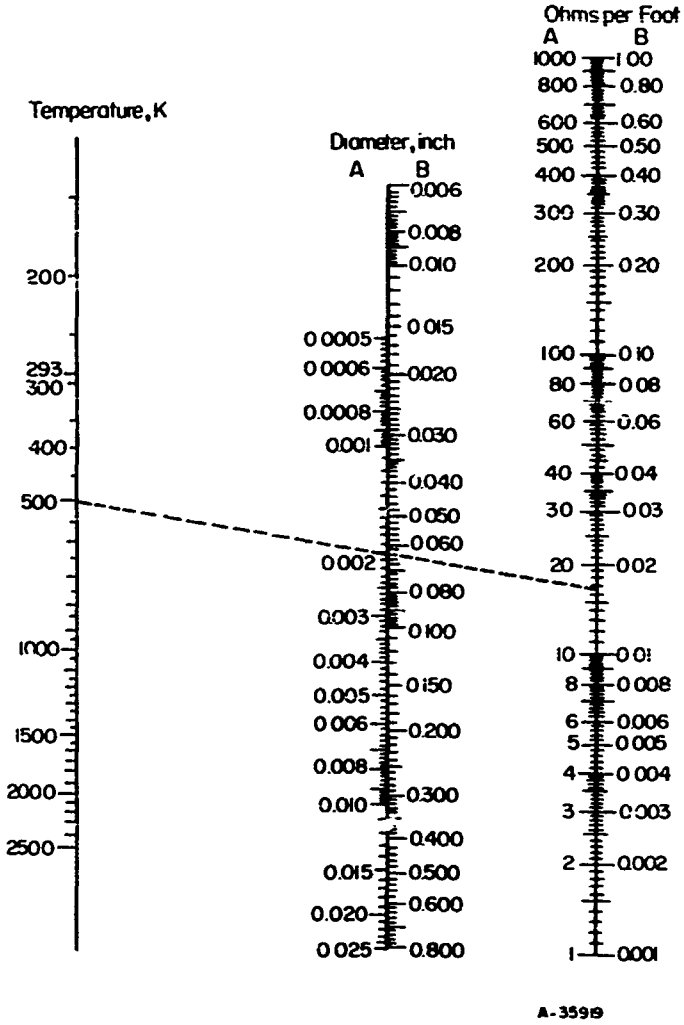


FIGURE A-4. ELECTRICAL RESISTANCE VERSUS TEMPERATURE NOMOGRAPH FOR UNALLOYED MOLYBDENUM[16]

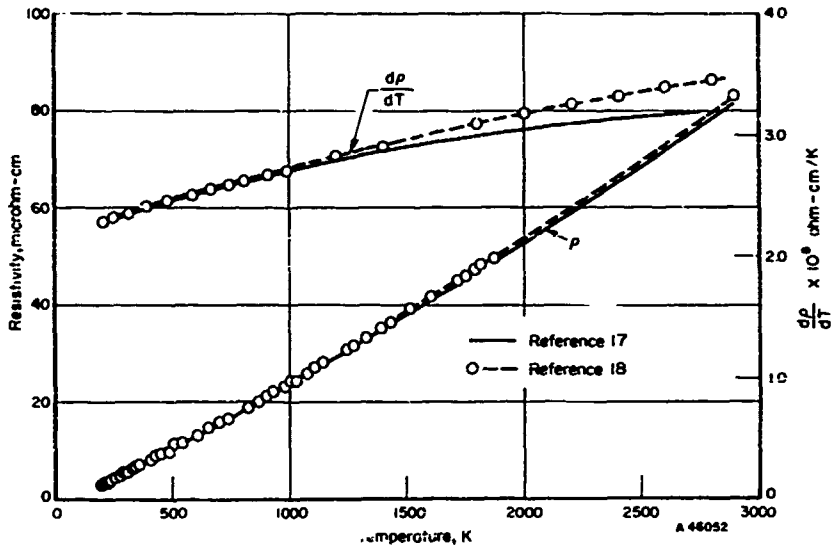


FIGURE A-5. ELECTRICAL RESISTIVITY OF MOLYBDENUM AND ITS TEMPERATURE COEFFICIENT

3. Mechanical Properties

a. Tensile Properties at Room Temperature

Ultimate tensile strength: Tables A-3 through A-10
Figures A-6 through A-11

Tensile yield strength: Tables A-3 through A-10
Figures A-6 through A-9

Elongation: Tables A-3 through A-10
Figures A-6 through A-8 and Figure A-11

Reduction in area: Table A-10
Figure A-6

Modulus of elasticity: 47×10^6 psi[12, 16]

b. Effect of Temperature on Tensile Properties

Ultimate tensile strength: Table A-11
Figures A-13 through A-17 and A-19 through A-21

Tensile yield strength: Table A-11
Figures A-12 through A-14 and A-16 through A-19

Elongation: Table A-11
Figures A-13, A-16, A-17, A-19, and A-20

Reduction in area: Table A-11
Figures A-12, A-13, A-16, and A-18

Modulus of elasticity: Tables A-11 and A-12
Figures A-22 and A-23

c. Notched Tensile Properties

Figures A-24 through A-33

d. Creep and Stress-Rupture Properties

Tables A-13 through A-16
Figures A-34 through A-44

e. Other Selected Mechanical Properties

Hardness: Table A-17
Figure A-45

Bend ductility: Table A-18

Compressive strength: Table A-19
Figures A-46 and A-47

Shear strength: Table A-20
Figure A-48

Impact strength: Figure A-49

Fatigue strength: Figures A-50 through A-52

TABLE A-3. MINIMUM TENSILE-PROPERTY REQUIREMENTS FOR ARC-CAST AND POWDER-METALLURGY MOLYBDENUM ROUND RODS[a][4]

Method of Consolidation	Condition	Diameter, inches	Minimum Tensile Strength, 1000 psi	Minimum Yield Strength (0.2% Offset), 1000 psi	Minimum Elongation in 1 Inch, per cent
AC or PM	Stress relieved	0.020 to 1/8, incl.	85	65	15[b]
		Over 1/8 to 13/32	75	55	15
		Over 13/32 to 7/8	90	75	18
		Over 7/8 to 1-1/8	85	70	15
		Over 1-1/8 to 1-7/8	75	65	10
		Over 1-7/8 to 2-7/8	70	60	10
		Over 2-7/8 to 3-1/2	65	55	10
AC	Recrystallized	Under 2	60	35	20
		2 to 3-1/2	55	25	20

(a) Properties shall be determined using a test rate of 0.002 to 0.005 inch per inch per minute through 0.6 per cent offset, then 0.02 to 0.05 inch per inch per minute to fracture.

(b) In 10 inches.

TABLE A-4. TENSILE-PROPERTY REQUIREMENTS FOR ARC-CAST AND POWDER-METALLURGY MOLYBDENUM STRIP, SHEET, FOIL, AND PLATE[a][3]

Tensile Strength Range, 1000 psi	Minimum Yield Strength (0.2% Offset), 1000 psi	Minimum Elongation in 2 Inches, per cent	
		Equal to or Less Than 0.020 in.	Greater Than 0.020 in.
60-85	45	5	10
85-110	70	5	10
110-135	90	3	5
135-160	110	2	5

(a) Properties shall be determined using a test rate of 0.002 to 0.005 inch per inch per minute through 0.6 per cent offset, then 0.02 to 0.05 inch per inch per minute to fracture.

TABLE A-5. TYPICAL ROOM-TEMPERATURE TENSILE DATA FOR ARC-CAST STRESS-RELIEVED MOLYBDENUM ROUND BAR PRODUCED BY CLIMAX[a][19]

Diameter, inches	Average Tensile Strength, 1000 psi	Average Yield Strength (0.2% Offset), 1000 psi	Average Elongation In 1 Inch, per cent
1/4	105	96	37
1/2	105	95	35
5/8	99	90	35
3/4	92	84	15
7/8	93	86	30
1	98	85	30
1-1/8	96	87	35
1-1/4	89	76	26
1-1/2	92	80	20
1-3/4	85	78	20
2	82	75	40
2-1/8	84	74	34
2-1/2	82	74	28
2-3/4	80	70	20
4	78	68	27

(a) Cold Water Production Facility. All data from 6-inch-diameter arc-cast ingots covering a 3-year period. Material stress relieved 1/4 to 1-1/2 hours at 1700 to 1850 F. Test rate 0.002 inch per inch per minute in the elastic range, then 0.05 inch per inch per minute to fracture.

TABLE A-6. ROOM-TEMPERATURE TENSILE PROPERTIES OF UNIVERSAL CYCLOPS ARC-CAST MOLYBDENUM PLATE AND SHEET PRODUCTS[a][9, 10]

Property	Minimum	Typical
Plate, Over 3/16 Inch to 1/2 Inch		
Tensile Strength, 1000 psi	90	105
Yield Strength (0.2% Offset), 1000 psi	85	95
Elongation in 2 Inches, per cent	5	8
Plate, Over 1/2 Inch to 1-1/2 Inches		
Tensile Strength, 1000 psi	85	100
Yield Strength (0.2% Offset), 1000 psi	80	90
Elongation in 2 Inches, per cent	4	6
Sheet, 0.020 Inch and Under		
Tensile Strength, 1000 psi	90	105
Yield Strength (0.2% Offset), 1000 psi	85	100
Elongation in 2 Inches, per cent	8	12
Sheet, Over 0.020 Inch		
Tensile Strength, 1000 psi	95	110
Yield Strength (0.2% Offset), 1000 psi	85	100
Elongation in 2 Inches, per cent	10	14

(a) Test rate 0.05 inch per inch per minute.

TABLE A-7. ROOM-TEMPERATURE TENSILE PROPERTIES OF SYLVANIA POWDER-METALLURGY STRESS-RELIEVED MOLYBDENUM PLATE AND SHEET PRODUCTS[a][11]

Property	Minimum	Typical
Plate		
Tensile Strength, 1000 psi	75	90
Yield Strength (0.2% Offset), 1000 psi	65	70
Elongation in 2 Inches, per cent	2.5	4
Sheet		
Tensile Strength, 1000 psi	90	100
Yield Strength (0.2% Offset), 1000 psi	85	90
Elongation in 2 Inches, per cent	10	13

(a) Test rate 0.005 inch per inch per minute to 0.6 per cent offset, then 0.05 inch per inch per minute to fracture.

TABLE A-8. ROOM-TEMPERATURE TENSILE PROPERTIES OF CLIMAX ARC-CAST MOLYBDENUM SHEET (1/16 INCH)[20]

Property	Stress Relieved		Recrystallized	
	Long.	Trans.	Long.	Trans.
Tensile Strength, 1000 psi				
Minimum	91.3	91.5	62.2	58.2
Maximum	105.5	106.2	66.5	66.0
Yield Strength (0.2% Offset), 1000 psi				
Minimum	79.7	82.7	45.5	43.7
Maximum	90.8	93.8	61.3	58.5
Elongation, per cent				
Minimum	20	16	40	16
Maximum	27	24	58	49

TABLE A-9. ROOM-TEMPERATURE TENSILE PROPERTIES OF POWDER-METALLURGY TUBING[a][21]

Temper	Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation in 2 Inches, per cent
Recrystallized	65 max	50 max	5 min
Stress relieved	85 max	60-85	8 min
Half-hard	85-130	75-110	2 min

(a) For tubing having 1/8-inch OD or larger and 0.015-inch wall or heavier. Typical analyses 0.015% C max, 0.007% O max, 0.003% N max, 0.020% Fe, 0.010% Ni, and 0.010% Si.

TABLE A-10. SOME SELECTED ROOM-TEMPERATURE TENSILE PROPERTIES OF MOLYBDENUM

Condition	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation, per cent	Reduction in Area, per cent	Reference
Recrystallized bar (7/16 inch)[a]	67.2	65.9	23	19.9	(22)
	67.7	60.4	21	18.5	(22)
Stress-relieved rod (5/8 inch)[b]	114.4	--	39	67.6	(23)
	116.5	--	37	68.2	(23)
As-rolled rod (5/8 inch)[c]	102.2	78.8[d]	40	61	(24)
Stress-relieved rod (5/8 inch)[c]	97.2	82.9[d]	42	69	(24)
Recrystallized rod (5/8 inch)[c]	68.2	55.9	42	37.8	(24)
Rolled square bar (1/2 inch)[e]					
6.1%, 1800 F	73.6	55.6	56	57.9	(25)
8.6%, 1800 F	73.3	57.1	53	33.7	(25)
17.1%, 1800 F	76.8	61.4	56	53.1	(25)
26.1%, 1800 F	80.9	66.2	40	59.4	(25)
48.8%, 1800 F	91.5	83.5	41	65.4	(25)
79.3%, 1800 F	98.9	82.6	24	23.2	(25)
5.6%, 2200 F	74.6	62.8	45	47.1	(25)
10.4%, 2200 F	76.2	66.2	42	37.1	(25)
16.6%, 2200 F	80.6	69.9	36	43.3	(25)
26.6%, 2200 F	84.0	71.4	23	20.4	(25)
48.3%, 2200 F	92.7	81.4	11	11.6	(25)
79.3%, 2200 F	98.6	89.1	24	27.3	(25)
Cold-swaged material (88%)[f]	97.1	95	18	--	(26)
As-cast material	24.3	--	0	0	(27)
As extruded (2 inches)	70.9	62.7	1	0.8	(27)
As-rolled round (2 inches)	82.3	76.3	23	33.3	(27)
As-rolled round (1 inch)	92.4	72.2	36	30	(27)
As-rolled Round (5/8 inch)	109.3	84.7	36	36	(27)

(a) 0.002% C.
(b) 0.030% C.
(c) 0.015% C.
(d) 0.1 per cent offset.
(e) 0.025% C.
(f) 0.003% O, 0.0003% H, 0.001% N, and 0.05% C.

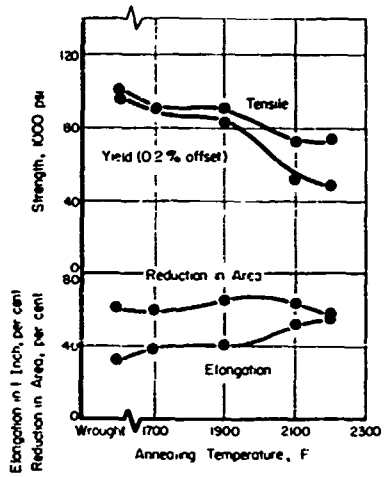


FIGURE A-6. EFFECT OF ANNEALING TEMPERATURE ON THE ROOM-TEMPERATURE TENSILE PROPERTIES OF COMMERCIAL-PURITY ARC-CAST MOLYBDENUM BAR (1/4-INCH DIAMETER)[28]

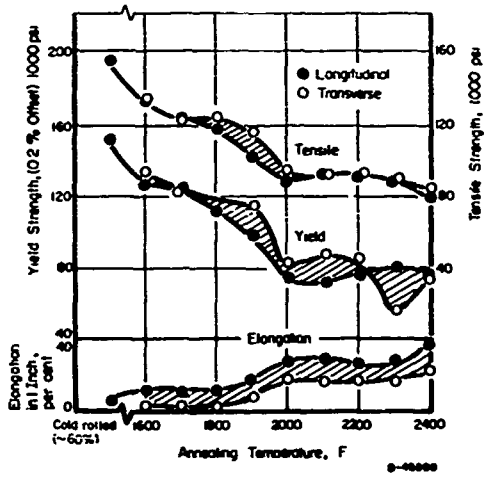


FIGURE A-7. EFFECT OF ANNEALING TEMPERATURE ON THE ROOM-TEMPERATURE TENSILE PROPERTIES OF COMMERCIAL-PURITY ARC-CAST MOLYBDENUM SHEET (0.020 INCH)[28]

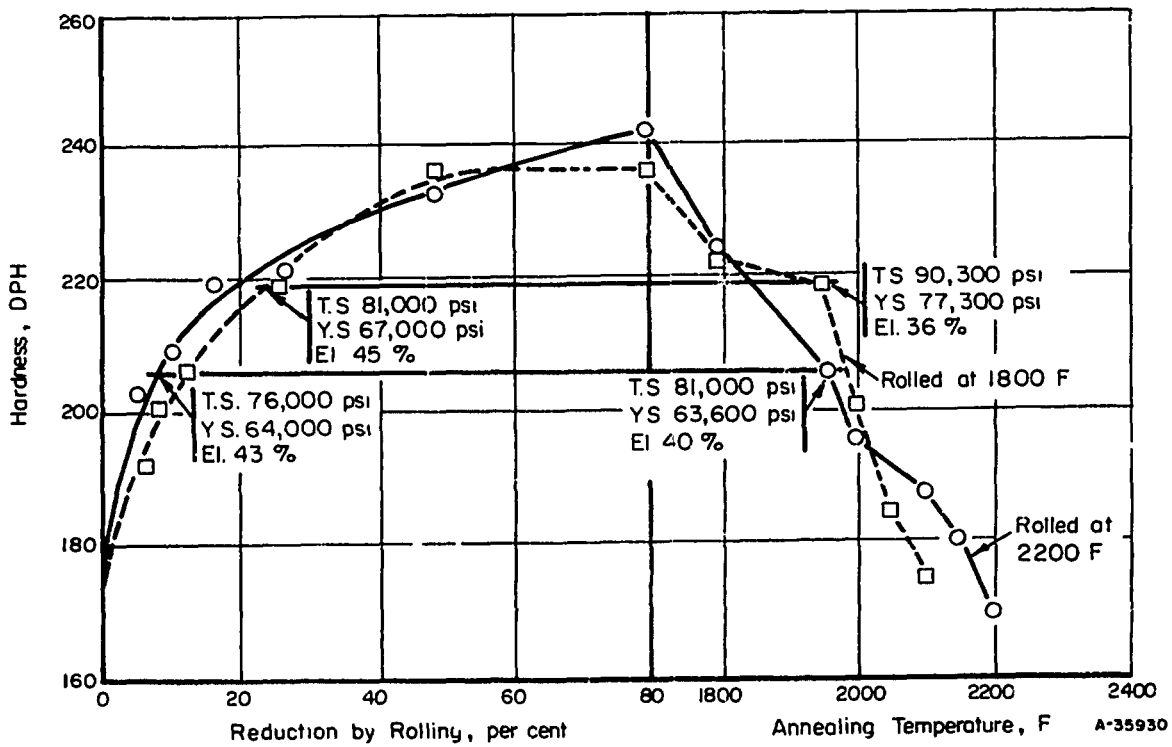


FIGURE A-8. COMPARISON OF TENSILE PROPERTIES OBTAINED BY COLD WORKING TO A GIVEN HARDNESS WITH THOSE OBTAINED BY ANNEALING TO THE SAME HARDNESS[25]

Test rate: 3 per cent/hour in elastic range
60 per cent/hour in plastic range.

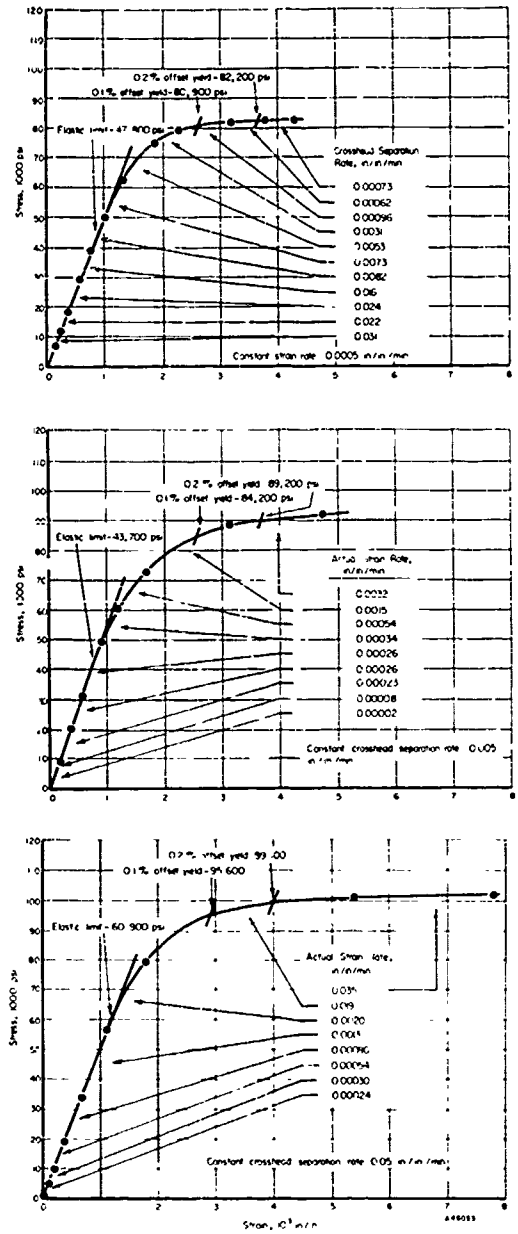


FIGURE A-9. EFFECT OF STRAIN RATE ON THE ROOM-TEMPERATURE STRENGTH PROPERTIES OF ARC-CAST STRESS-RELIEVED (1/2 HOUR AT 1800 F) MOLYBDENUM BAR[29]

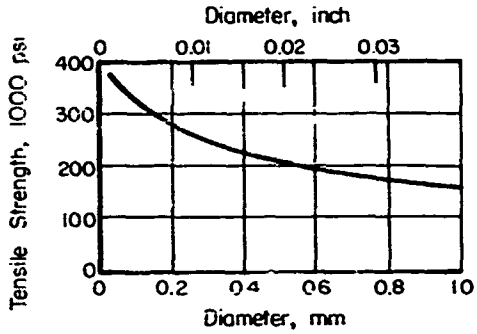


FIGURE A-10. RELATION BETWEEN TENSILE STRENGTH AND DIAMETER FOR DRAWN MOLYBDENUM WIRE[30]

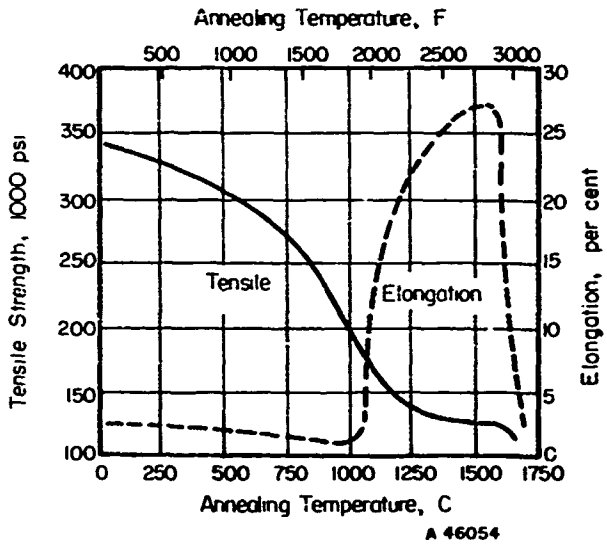


FIGURE A-11. TENSILE STRENGTH AND ELONGATION OF MOLYBDENUM WIRE (0.004-INCH DIAMETER) AS A FUNCTION OF THE ANNEALING TEMPERATURE[30]

TABLE A-11. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF POWDER-METALLURGY AND ARC-CAST SECTIONS TAKEN FROM MOLYBDENUM FORGINGS[a][31]

Section[b]	Temperature, F	Tensile Strength, 1000 psi		Yield Strength (0.2% Offset), 1000 psi		Elongation in 1 inch, per cent		Reduction in Area, per cent		Modulus of Elasticity, 10^6 psi	
		Axial	Tang.	Axial	Tang.	Axial	Tang.	Axial	Tang.	Axial	Tang.
PM Ring, Supplier 1	RT	86.7	82.8	83.0	73.6	--	40.3	--	58.9	49.9	43.2
	500	63.3	61.5	61.5	58.7	20.7	26.0	60.5	68.4	46.6	43.6
	1000	58.8	53.4	57.8	51.8	19.7	20.0	69.3	77.6	40.5	38.4
	2000	42.0	37.3	39.3	36.4	17.3	20.0	78.3	84.8	34.6	27.3
	3000	7.38	7.53	5.04	5.22	28.0	32.3	68.5	83.8	8.0	5.9
	4300	1.60	1.69	1.42	1.61	18.0	26.0	--	88.3	2.0	1.7
PM Ring, Supplier 2	RT	96.3	95.8	86.3	89.1	39.3	40.3	61.7	58.3	46.8	45.0
	500	64.4	66.2	55.1	59.3	34.7	31.0	65.1	77.2	42.2	40.9
	1000	54.4	55.4	51.5	52.5	22.3	23.0	68.2	75.5	38.8	38.0
	2000	34.8	21.4	33.9	16.3	24.7	30.5	>90	>90	21.6	15.4
	3000	5.6	5.0	4.4	3.7	31.7	25.7	82[c]	80[c]	10.4	7.1
	4300	1.0	1.2	0.9	1.2	11.0	13.7	28.0	43.8	1.6	1.7
AC Ring, Supplier 2	RT	86.1	89.1	84.7	81.4	31.3	32.5	52.3	48.8	46.0	42.7
	500	55.7	57.8	36.6	44.1	35.3	35.0	77.3	66.9	34.9	39.7
	1000	43.8	44.8	31.2	34.1	32.3	30.0	80.8	71.8	32.3	35.3
	2000	28.7	34.3	22.2	31.0	28.3	24.3	89.2	89.1	25.8	27.9
	3000	5.49	6.10	3.51	3.87	34.3	37.3	91.0	>90	8.4	7.6
	4500	0.614	0.461	0.508	0.384[d]	--	--	--	--	1.2	1.2
AC Liner, Supplier 2	75	77.0[e]	75.6[e]	76.1[e]	75.5[e]	21.0[e]	17.0[e]	23.9[e]	14.6[e]	46.6[e]	41.7[e]
	500	46.9	43.2	40.2	37.0	33.7	32.0	80.2	76.9	41.9	40.9
	1000	37.0	40.5	34.0	38.7	29.4	25.7	84.4	79.8	38.6	45.6
	2000	30.1	30.6	29.8	30.1	20.4	21.7	>90	>90	38.0	36.1
	3000	5.37	5.18	3.89	3.71	31.7	30.0	>90	>90	9.8	11.0
	4500	0.562	0.582	0.415	0.443	2.6	2.5	--	--	1.1	1.0

(a) Data given are the average of three tests. Test rate 0.005 inch per inch per minute to 0.6 per cent offset, then 0.05 inch per inch per minute to fracture for room-temperature tests. All elevated-temperature tests were conducted in argon, heated by resistance at 100 F per second, held at temperature for 30 seconds, and then loaded at a rate of 0.05 inch per inch per minute to fracture.

(b) Chemical analyses PM Ring, Supplier 1, 0.020% Si, <0.001% Ni, 0.003% Fe, <0.001% Mn, <0.001% Mg, <0.001% Cr, 0.003% W, 0.002% Sn, 0.001% Cu, <0.001% Ca, and 0.001% Al. PM Ring, Supplier 2, 0.008% C, 0.001% Si, 0.001% Ni, 0.003% Fe, 0.001% Mn, 0.001% Mg, 0.001% Cr, 0.003% W, 0.001% Sn, 0.001% Cu, 0.001% Ca, 0.001% Al, 0.0022% O, 0.0006% H, and 0.0006% N. AC Ring, Supplier 2, 0.020-0.028% C, 0.003-0.005% Si, 0.001% Ni, 0.001-0.002% Fe, 0.0003-0.0007% O, 0.00001-0.00002% H, and 0.0001-0.0004% N. AC Liner, Supplier 2, 0.015% C, 0.002% Si, 0.001% Ni, 0.002% Fe, 0.0002% O, 0.001% H, and 0.0001% N. A schematic diagram showing forging procedures used is given below:

PM Ring, Supplier 1	AC Ring, Supplier 2	AC Liner, Supplier 2
Billet	Billet	Billet
Upset	Upset	Block & pierce
Recrystallize	Back extrude	Shape
Upset	Stress relieve	Stress relieve
Punch	Part & face rings	
Cup	Shape	
Stress relieve	Stress relieve	
Part and rough machine ring		
Ring roll		
Stress relieve		

(c) One test.

(d) Two tests.

(e) Four tests.

TABLE A-12. EFFECT OF TEMPERATURE ON THE MODULUS OF ELASTICITY OF MOLYBDENUM

Temperature, F	Modulus of Elasticity, 10^6 psi	
	Ref. (16)	Ref. (32)[a]
RT	47	40.8
400	--	35.1
500	44	--
600	--	36.1
800	--	34.9
1000	42	31.0
1200	--	32.9
1400	--	27.2
1600	--	25.6
1800	--	25.4
2000	38	21.4
2200	--	17.4
2400	--	8.55
3000	15	--
3750	4	--
4500	0.2	--

(a) From 3/14-inch-diameter arc-cast hot-cold-rolled stress-relieved bar. Data from compression tests conducted in argon at 0.05 inch per minute.

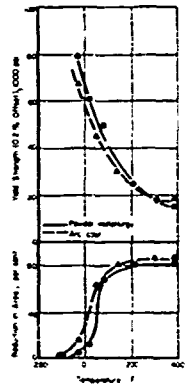


FIGURE A-12. LOW-TEMPERATURE STRENGTH AND DUCTILITY OF COMMERCIAL-PURITY POWDER-METALLURGY AND ARC-CAST RECRYSTALLIZED MOLYBDENUM BAR (5/8-INCH DIAMETER)[28]

Rolled 1650 to 1830 F from 2-1/8-inch square to 5/8-inch round, recrystallized 2190 F.

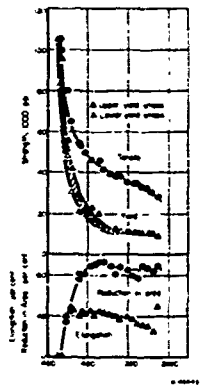


FIGURE A-13. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF COMMERCIAL-PURITY SWAGED AND RECRYSTALLIZED MOLYBDENUM BAR (1/4-INCH DIAMETER)[33]

Recrystallized 20 minutes at 2800 F.

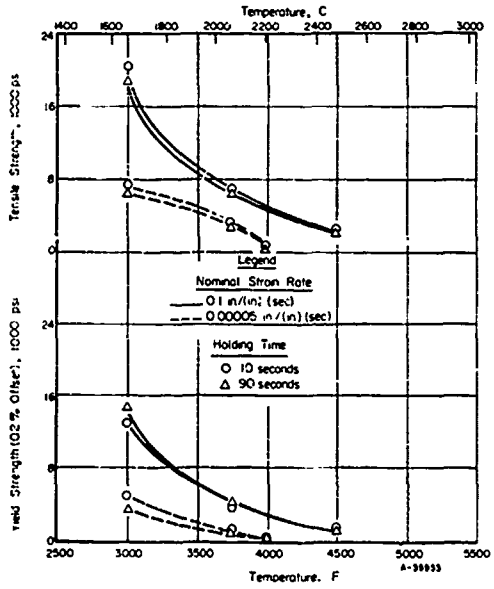


FIGURE A-14. HIGH-TEMPERATURE STRENGTH OF ARC-CAST MOLYBDENUM SHEET AT DIFFERENT STRAIN RATES AND HOLDING TIMES[34]

Specimens were heated to test temperature within 20 seconds and tested in argon.

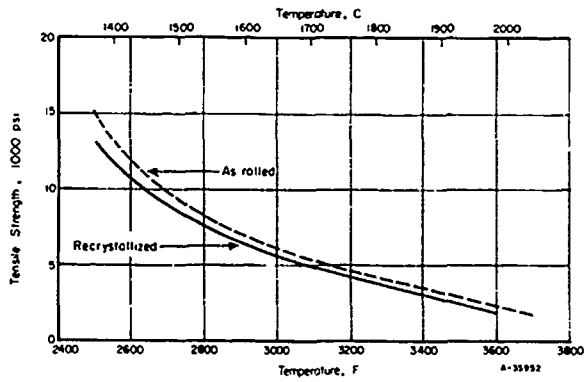


FIGURE A-15. EFFECT OF TEMPERATURE ON THE SHORT-TIME TENSILE STRENGTH OF ROLLED AND RECRYSTALLIZED ARC-CAST MOLYBDENUM[35]

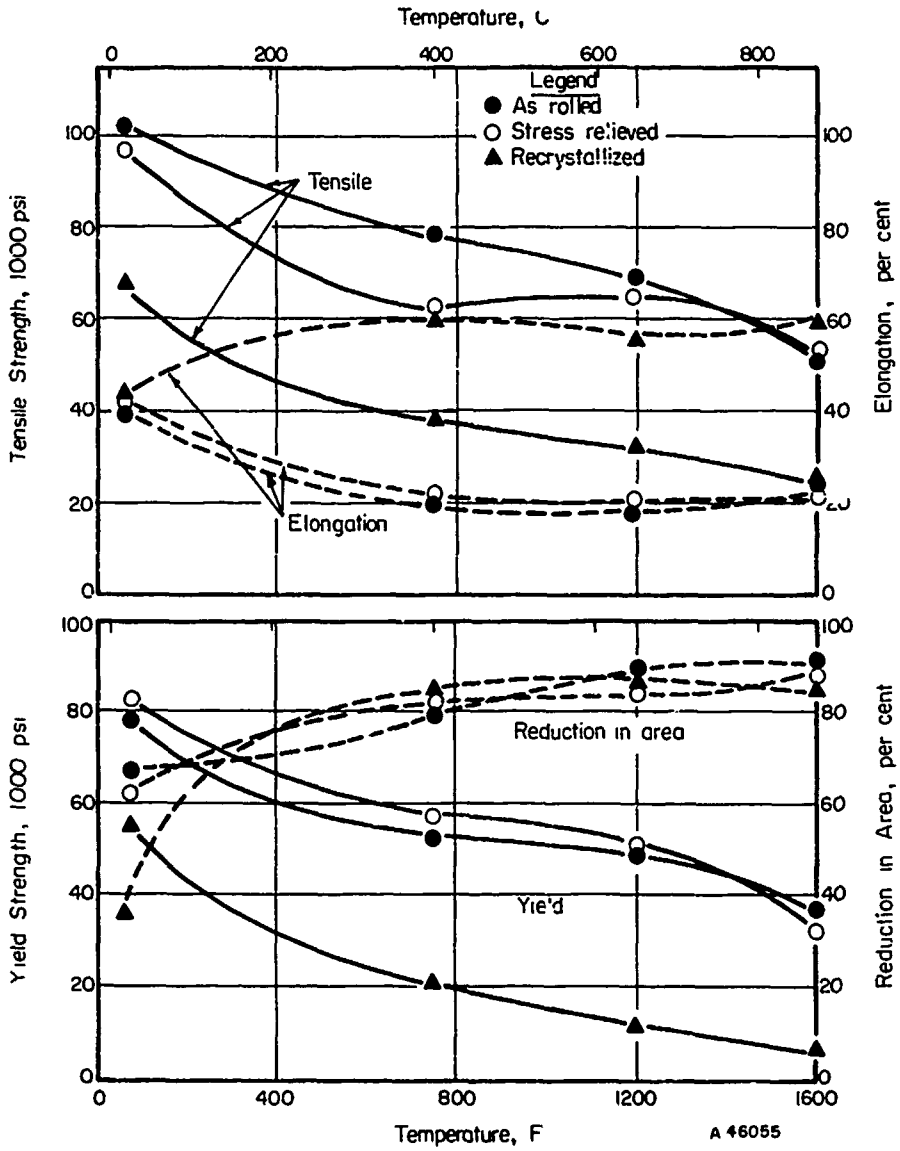


FIGURE A-16. EFFECT OF THERMAL TREATMENT AND TEST TEMPERATURE ON THE PROPERTIES OF MOLYBDENUM[24]

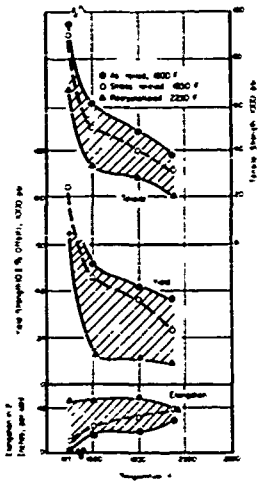


FIGURE A-17. EFFECT OF TEMPERATURE AND THERMAL TREATMENT ON THE TENSILE PROPERTIES OF COMMERCIAL-PURITY ARC-CAST MOLYBDENUM BAR (7/8-INCH DIAMETER)[28]

Aluminum coated tested in air.

Test rate 1000 psi per minute.

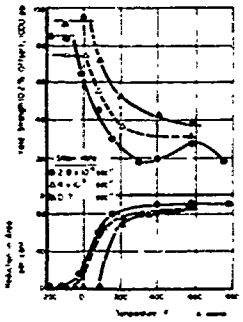


FIGURE A-18. EFFECT OF STRAIN RATE ON THE LOW-TEMPERATURE STRENGTH AND DUCTILITY OF COMMERCIAL-PURITY RECRYSTALLIZED POWDER-METALLURGY MOLYBDENUM BAR (5/8-INCH DIAMETER)[24]

Recrystallized 1 hour at 2100 F.

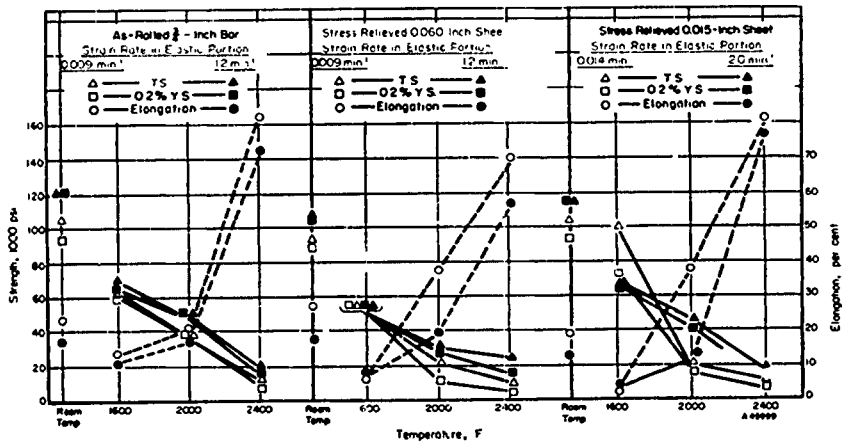


FIGURE A-19. EFFECT OF STRAIN RATE ON THE ELEVATED-TEMPERATURE TENSILE PROPERTIES OF ARC-CAST MOLYBDENUM BAR AND SHEET(36)

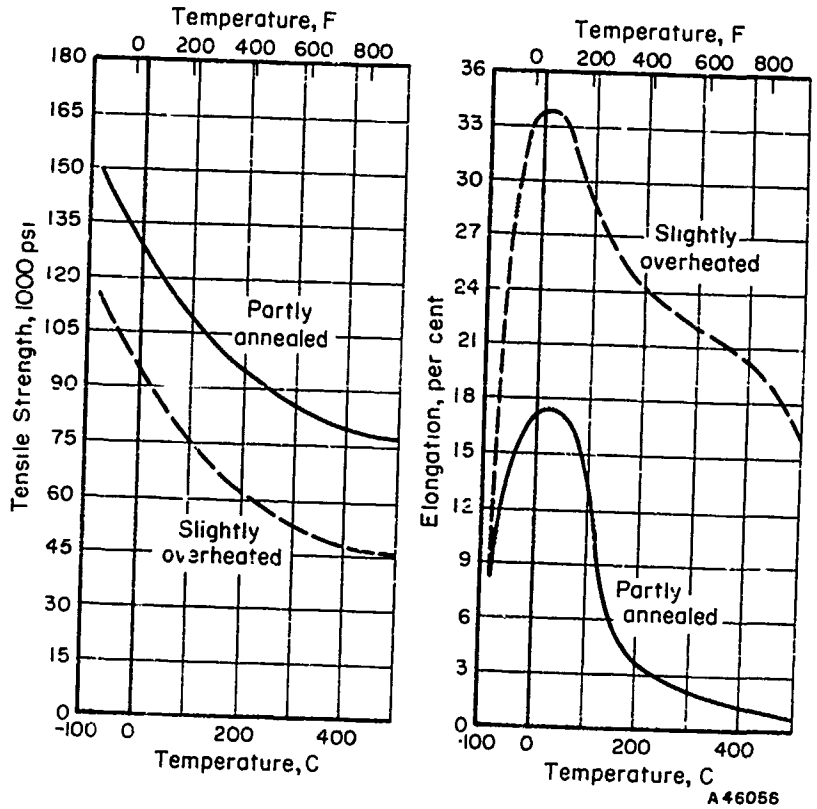


FIGURE A-20. TENSILE STRENGTH AND ELONGATION OF MOLYBDENUM WIRE (0.012-INCH DIAMETER) AS A FUNCTION OF THE TEMPERATURE FOR DIFFERENT ANNEALING CONDITIONS[30]

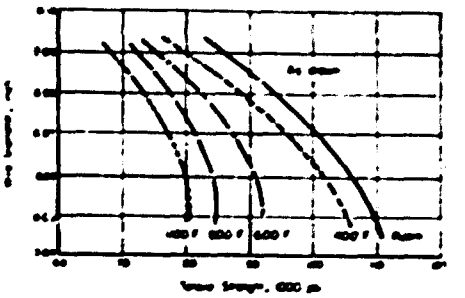


FIGURE A-21. EFFECT OF TEMPERATURE ON THE TENSILE STRENGTH OF MOLYBDENUM WIRE AS A FUNCTION OF DIAMETER[37]

FIGURE A-22. EFFECT OF TEMPERATURE ON THE DYNAMIC MODULUS OF ELASTICITY[24]

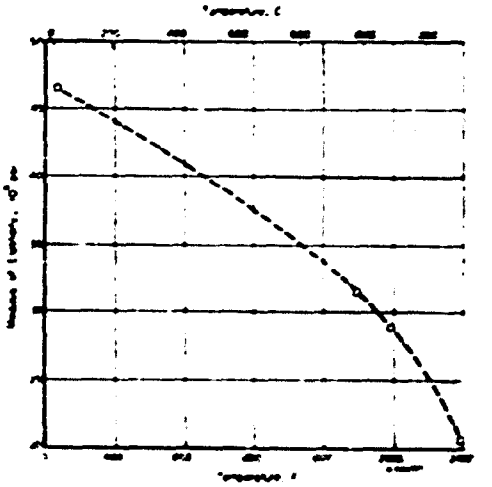


FIGURE A-23. EFFECT OF TEMPERATURE ON THE STATIC MODULUS OF ELASTICITY OF ARC-CAST MOLYBDENUM[23]

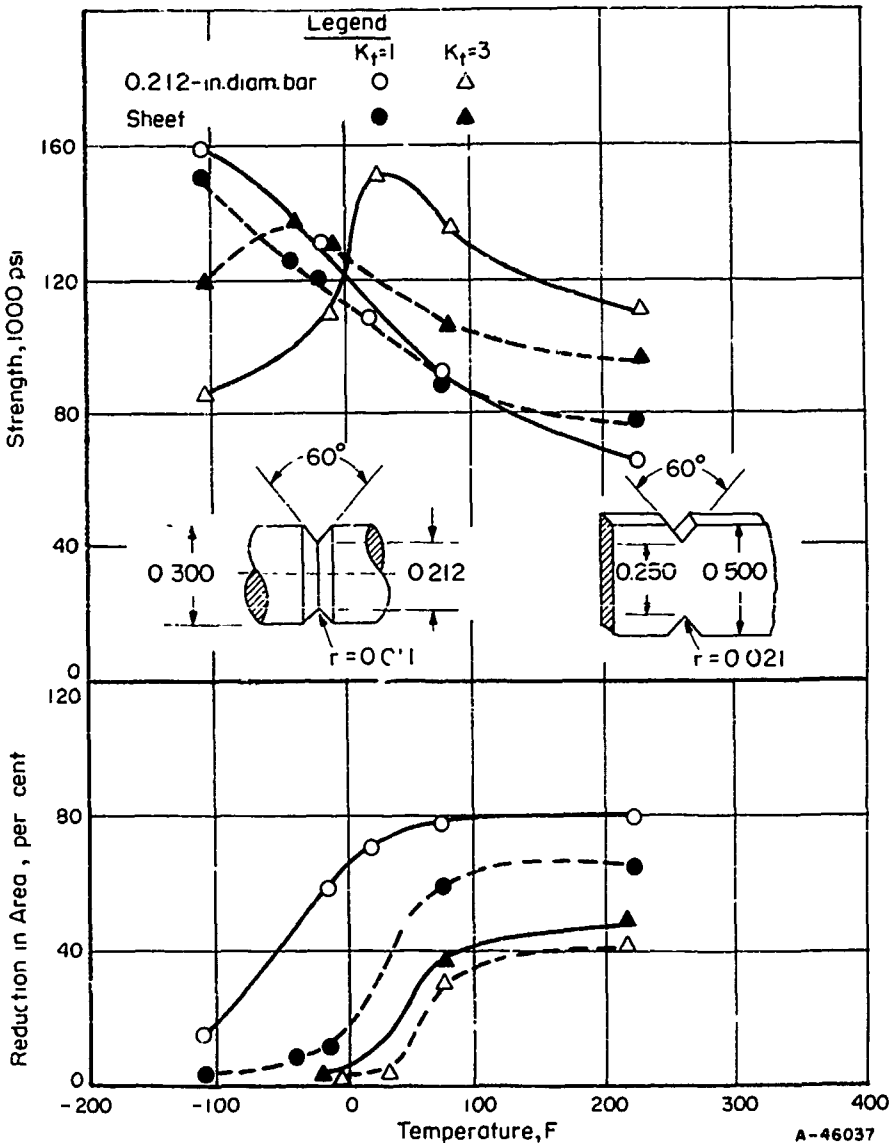


FIGURE A-24. UNNOTCHED AND NOTCHED STRENGTH AND DUCTILITY OF COMMERCIAL-PURITY ARC-CAST STRESS-RELIEVED MOLYBDENUM BAR AND SHEET[24]

Stress relieved 15 minutes at 1830 F.

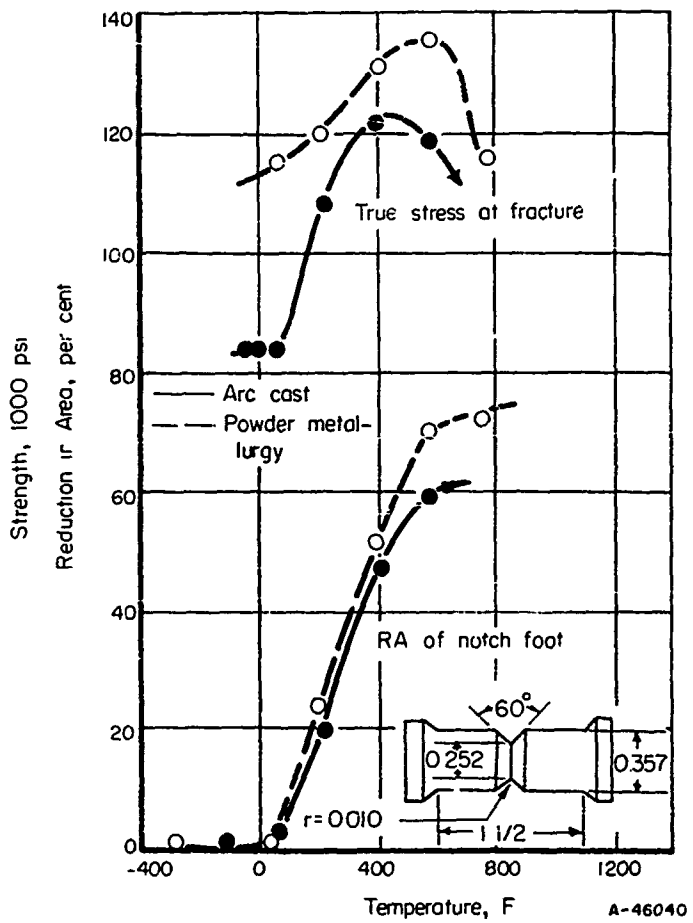


FIGURE A-25. NOTCHED STRENGTH AND DUCTILITY OF COMMERCIAL-PURITY ARC-CAST AND POWDER-METALLURGY MOLYBDENUM BAR[28]

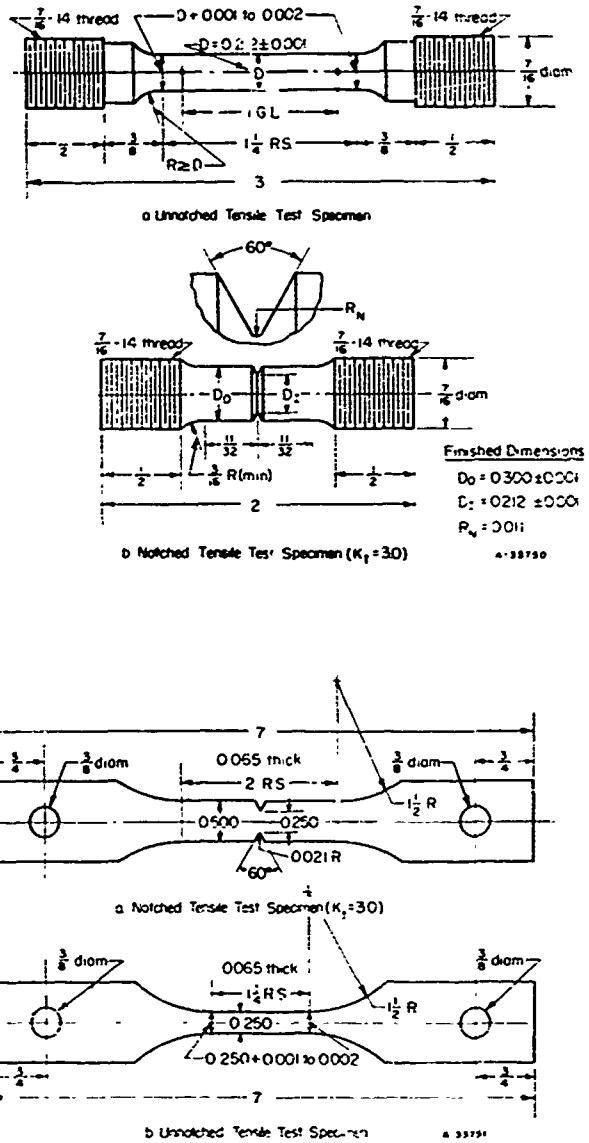


FIGURE A-26. UNNOTCHED AND NOTCHED BAR AND SHEET TENSILE TEST SPECIMENS USED TO OBTAIN DATA SHOWN IN FIGURES A-27 THROUGH A-30.

All dimensions are in inches.

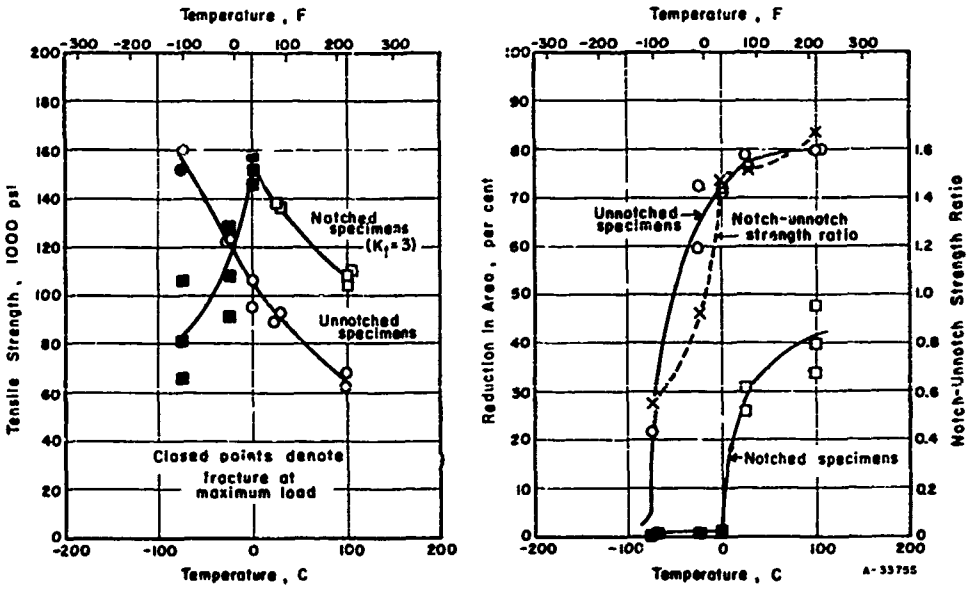


FIGURE A-27. TENSILE PROPERTIES FOR WROUGHT, STRESS-RELIEVED ARC-MELTED MOLYBDENUM BAR (1/4 HR AT 1000 C; HARDNESS 234 VHN)[22]

	Unnotched	Notched
Crosshead Speed, inch per minute	0.02	0.005

Impurity	Weight Per Cent
C	0.002
O	0.0022
N	0.001
H	0.00006
Ta	<0.2
W	<0.1
Others	<0.05

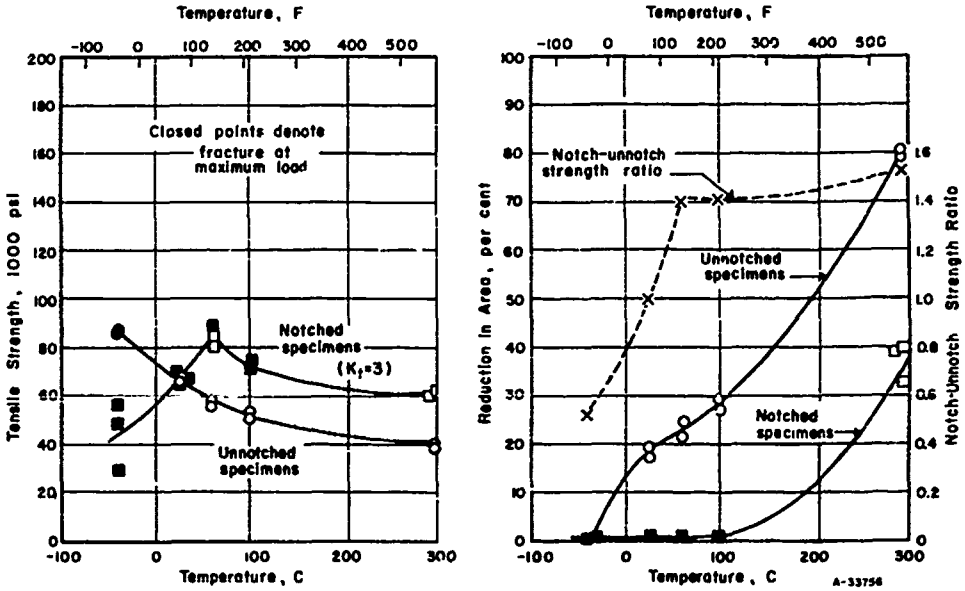


FIGURE A-28. TENSILE PROPERTIES FOR RECRYSTALLIZED ARC-MELTED MOLYBDENUM BAR (1 HR AT 1360 C; HARDNESS 188 VHN; ASTM 7.2)[22]

	Unnotched	Notched
Crosshead Speed, inch per minute	0.02	0.005

Impurity	Weight Per Cent
C	0.002
O	0.0022
N	0.001
H	0.00006
Ta	<0.2
W	<0.1
Others	<0.05

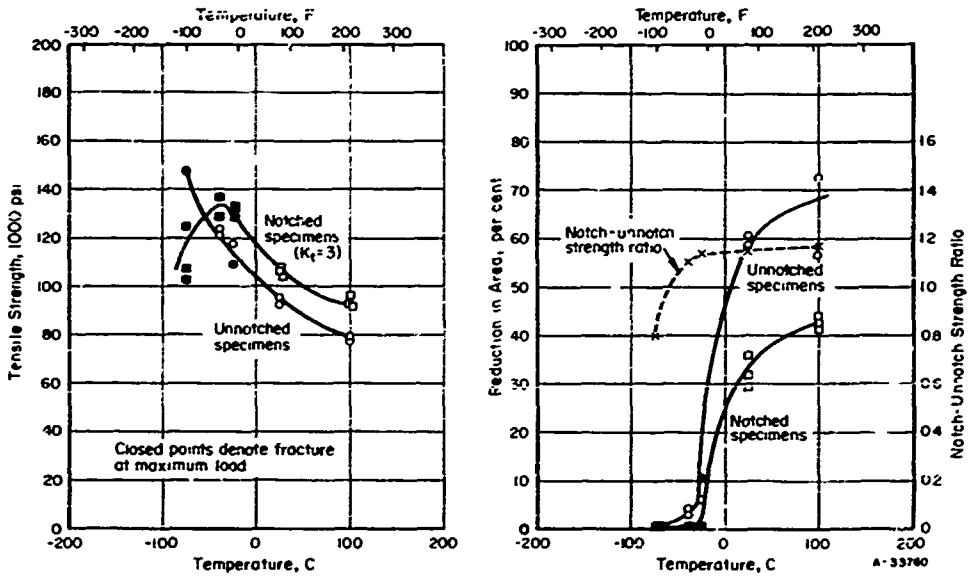


FIGURE A-29. TENSILE PROPERTIES FOR WROUGHT, STRESS-RELIEVED ARC-MELTED MOLYBDENUM SHEET (1/4 HR AT 1000 C; HARDNESS 222 VHN)[22]

	Unnotched	Notched
Crosshead Speed, inch per minute	0.02	0.005

Impurity	Weight Per Cent
C	0.026
O	0.0009
N	<0.001
H	0.00006
Ta	<0.2
W	<0.1
Others	<0.05

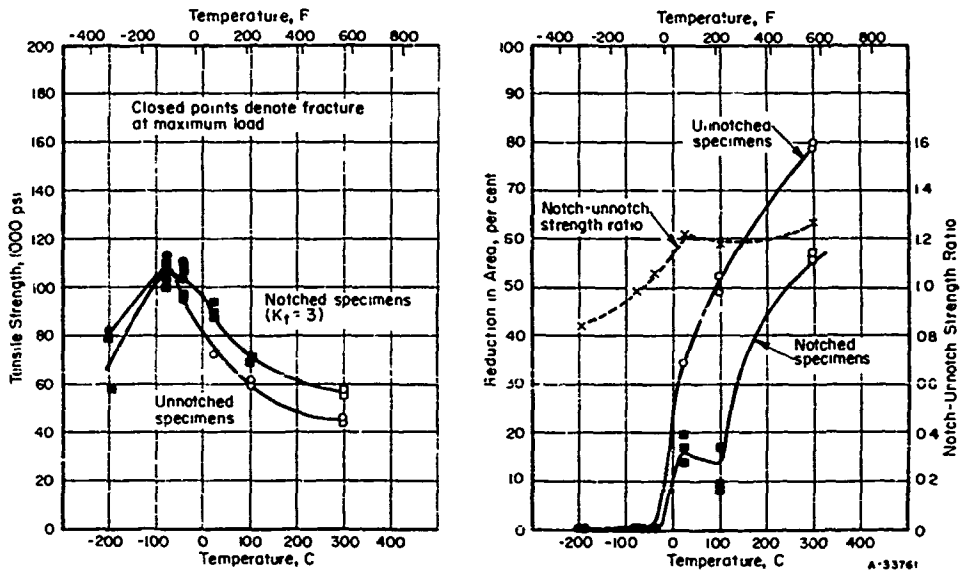


FIGURE A-30. TENSILE PROPERTIES FOR RECRYSTALLIZED ARC-MELTED MOLYBDENUM SHEET (1 1/4 HR AT 1300 C; HARDNESS 168 VHN, ASTM 7.1)[22]

	Unnotched	Notched
Crosshead Speed, inch per minute	0.02	0.005

Impurity	Weight Per Cent
C	0.026
O	0.0009
N	<0.001
H	0.00006
Ta	<0.2
W	<0.1
Others	<0.05

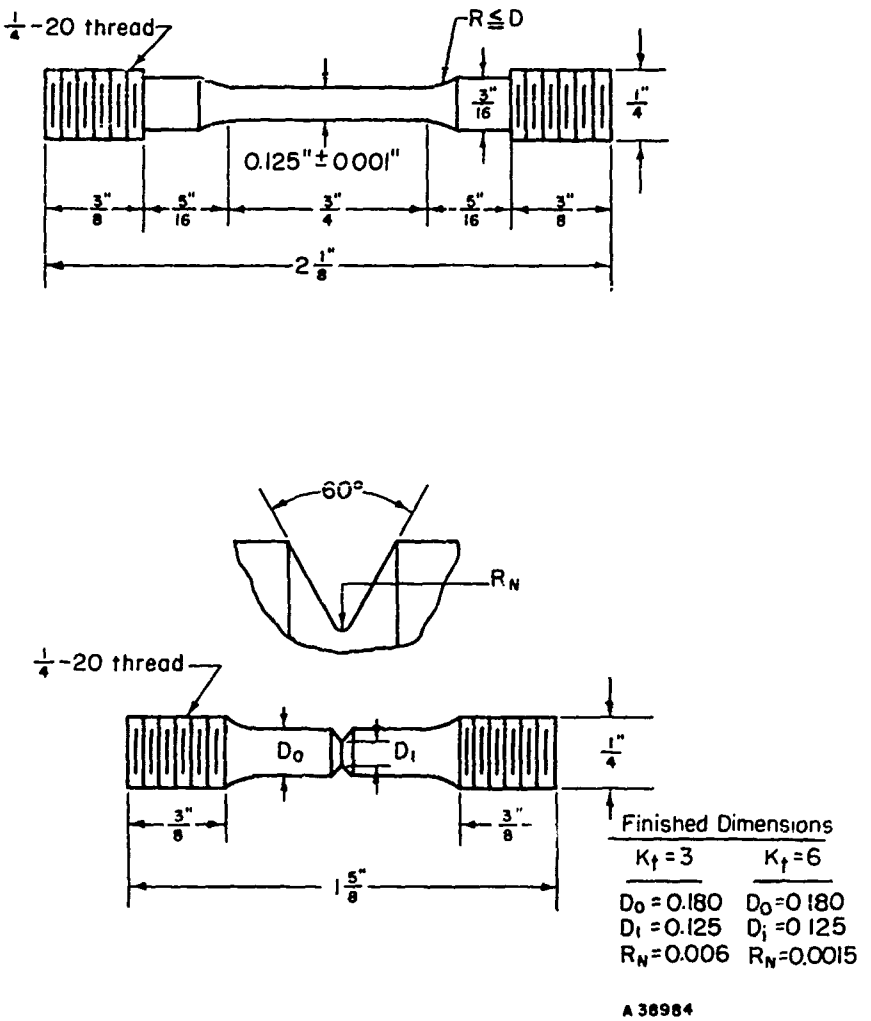


FIGURE A-31. UNNOTCHED AND NOTCHED BAR TENSILE TEST SPECIMENS USED TO OBTAIN DATA SHOWN IN FIGURES A-32 AND A-33

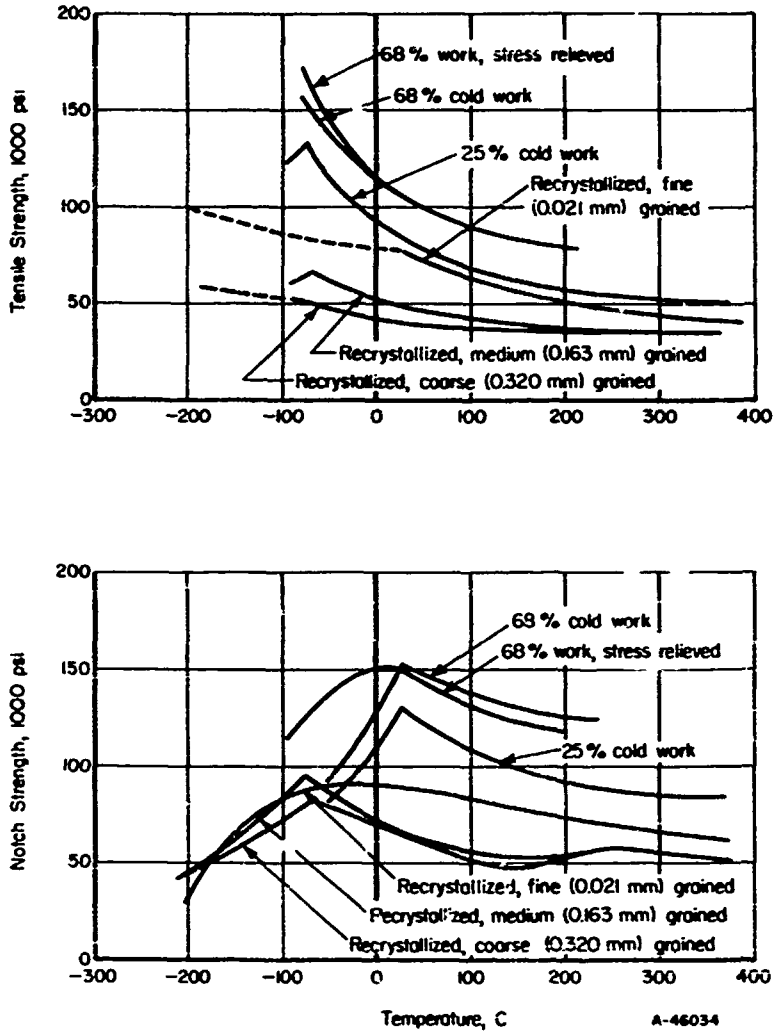


FIGURE A-32. EFFECT OF STRUCTURE ON THE UNNOTCHED AND NOTCHED TENSILE STRENGTH OF ARC-CAST MOLYBDENUM BAR[38]

	Unnotched	Notched	Impurity	PPM
Crosshead Speed, inch per minute	0.02	0.005	C	240-330
			O	5-6
			N	<10
			H	<1

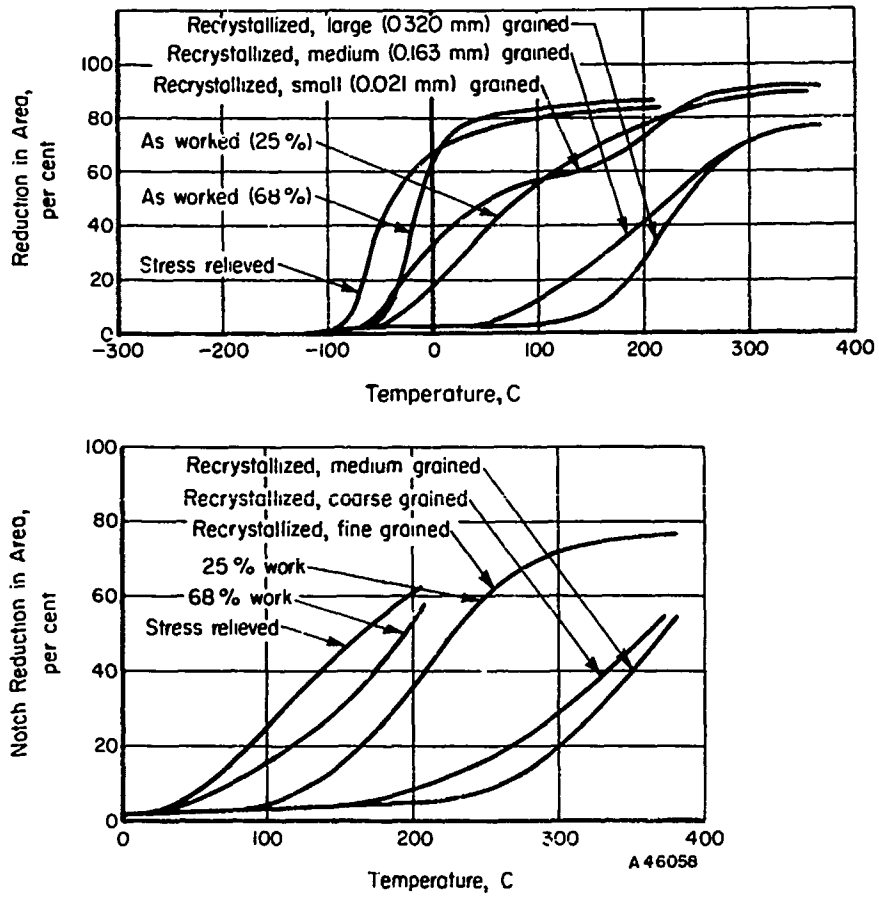


FIGURE A-33. EFFECT OF STRUCTURE ON THE UNNOTCHED AND NOTCHED REDUCTION IN AREA OF ARC-CAST MOLYBDENUM BAR[38]

	Unnotched	Notched	Impurity	PPM
Crosshead Speed, inch per minute	0.02	0.005	C	240-330
			O	5-6
			N	<10
			H	<1

TABLE A-13. CREEP AND RUPTURE CHARACTERISTICS OF FORGED ARC-CAST MOLYBDENUM AXIAL RINGS AT 1500 TO 4300 F[a](39)

Heat[b]	Temperature, F	Stress, 1000 psi	Time, sec, to Produce Indicated Amount of Deformation				Plastic Deformation in 1 Inch, per cent
			1%	3%	5%	Rupture	
0695	1500	50.5	127	153	154	155	23.0
0695		50.0	75	103	105	106	22.0
9917		39.0	36	84	123	151	27.0
9915		38.0	90	339	471	526	22.0
9915	2000	22.0	19	30	36	39	26.0
9915		22.0	79	127	147	161	26.0
9915		22.0	50	79	93	104	27.0
9915		21.75	118	171	194	205	28.0
9915		21.09	80	122	142	157	29.0
0695	2500	11.0	26	28	36	44	28.0
0695		9.8	11	70	207	372	31.0
9916		9.5	5	16	23	30	32.0
9916		9.2	12	32	53	253	30.0
9916		8.65	6	38	168	363	28.0
9915		6.94	209	209	1022	1116	30.0
0695	3000	5.6	14	24	40	53	34.0
0695		5.3	14	53	95	145	35.0
9917		5.0	5	17	27	66	37.0
9917		4.5	14	63	122	236	37.0
9917		3.86	21	124	247	431	34.0
9917		3.34	21	233	389	674	36.0
0695	3500	2.3	16	32	52	122	34.0
9916		2.2	13	73	97	175	30.0
0695		2.15	75	126	161	194	30.0
0695		2.15	15	63	101	188	30.0
0695		2.1	11	55	91	205	30.0
9916		2.05	9	39	80	182	29.0
0695	4000	1.0	18	32	51	70	29.0
0695		0.950	7	37	56	76	28.0
0695		0.900	15	46	71	104	30.0
0695		0.800	23	64	120	193	29.0
0695		0.860	8	83	120	162	29.0
0695		0.850	10	33	54	116	30.0
0695	4300	0.510	8	34	57	157	10.9
0695		0.500	31	81	123	296	12.0
0695		0.490	16	65	129	220	12.0
0695		0.480	9	26	41	107	14.3
0695		0.460	28	68	91	157	10.3
0695		0.450	30	94	163	257	10.3

(a) Specimens were loaded at room temperature and then resistance heated to temperature in approximately 20 seconds.
(b) Chemical analyses are given below:

Heat	Weight Per Cent						
	C	Si	Ni	Fe	O	H	N
0695	0.015	0.001	0.001	0.001	0.0002	0.0001	0.0001
9915	0.023	0.003	0.001	0.002	0.0003	0.00001	0.0001
9916	0.020	0.004	0.001	0.001	0.0004	0.00001	0.0001
9917	0.028	0.004	0.001	0.001	0.0007	0.00003	0.0004

TABLE A-14. CREEP AND RUPTURE CHARACTERISTICS OF FORGED POWDER-METALLURGY MOLYBDENUM AXIAL RINGS AT 1500 TO 4300 F[a][39]

Temperature, F	Stress, 1000 psi	Time, sec, to Produce Indicated Amount of Deformation				Plastic Deformation in 1 Inch, per cent
		1%	3%	5%	Rupture	
1500	41.85	49	54	55	59	19
	41.6	51	64	67	69	20
	41.6	164	289	296	299	19
	41.5	218	283	351	353	19
	40.8	695	1396	1575	1587	19
2000	36.8	5	6	8	8	21
	30.0	34	49	51	52	23
	29.8	9	20	22	26	26
	29.5	70	98	101	103	24
	28.6	62	117	124	132	21
	28.1	111	116	172	175	21
2500	12.0	17	27	35	62	31
	11.0	11	22	39	134	30
	10.0	10	35	80	143	29
	8.95	11	35	58	318	32
	8.95	39	85	153	286	31
	8.0	15	126	279	575	31
3000	6.0	6	13	19	42	31
	5.81	13	33	44	78	34
	5.44	11	41	84	205	29
	5.17	10	53	105	237	29
	5.0	12	76	135	295	30
	4.4	14	138	289	525	27
3500	2.8	17	41	47	52	33
	2.75	11	46	86	144	30
	2.7	23	57	[illegible]	106	31
	2.5	73	150	174	284	29
	2.2	101	303	369	386	28
	2.1	72	198	203	214	29
4000	1.98	11	22	26	27	29
	1.75	16	26	32	36	29
	1.5	28	62	67	74	29
	1.35	62	78	81	85	25
	1.30	29	61	65	71	27
	1.25	57	94	95	102	[illegible]
4300	0.864	31	39	--	40	--
	0.750	31	38	--	38	--
	0.680	52	53	--	53	--
	0.650	82	105	--	105	--
	0.580	100	119	--	200	--
	0.520	184	200	--	201	--

(a) Specimens were loaded at room temperature and then resistance heated to temperature in approximately 20 seconds. Chemical analyses 0.013% Si, 0.001% Ni, 0.002% Fe, 0.001% Mn, 0.001% Mg, 0.001% Cr, 0.003% W, 0.001% Sn, 0.001% Cu, 0.001% Ca, and 0.001% Al.

TABLE A-15. STRESS TO PRODUCE 5 PER CENT CREEP DEFORMATION IN 1 MINUTE FOR FORGED ARC-CAST AND POWDER-METALLURGY AXIAL MOLYBDENUM RINGS AT DIFFERENT TEMPERATURES[39]

Temperature, F	Stress, 1000 psi, to Produce 5 Per Cent Creep Deformation	
	Arc Cast	Powder Metallurgy
1500	43.0	41.9
2000	22.3	29.6
2500	9.8	10.6
3000	5.1	5.45
3500	2.26	2.85
4000	0.960	1.54
4300	0.492	0.720[a]

(a) Specimen ruptured before 5 per cent creep deformation. Result shown is stress to produce 2 per cent deformation in 1 minute.

TABLE A-16. RUPTURE PROPERTIES OF WROUGHT GRAIN-REFINED MOLYBDENUM SHEET[a][40]

Temperature, F	Sheet Thickness, inch	Stress, 1000 psi	Time to Rupture, minutes	Elongation in 2 Inches, per cent
2700	0.060	10.0	4.8	5.9
	0.059	8.0	11.8	12.5
	0.059	6.0	61.3	14.2
3000	0.060	7.0	1.1	3.0
	0.060	4.1	6.6	8.6
	0.060	4.1	13.4	9.4
	0.061	1.9	102.8	14.8

(a) 6-inch diameter ingot, forged to sheet bar at 2050 to 2250 F; 1-inch sheet bar rolled to 1/4-inch plate at 1300 F, annealed at 2100 F, and rolled to final sheet thickness starting at 1000 F and finishing at room temperature.

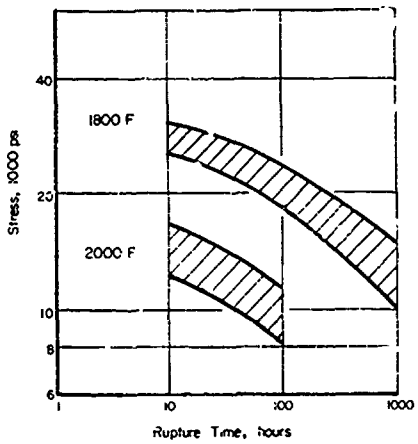


FIGURE A-34. RUPTURE-STRENGTH RANGE FOR COMMERCIAL-PURITY STRESS-RELIEVED MOLYBDENUM BAR (5/8- TO 1-INCH DIAMETER) AT 1800 AND 2000 F[41]

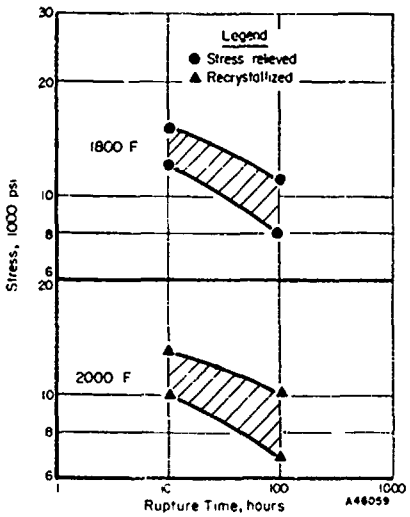


FIGURE A-35. RUPTURE-STRENGTH RANGE FOR COMMERCIAL-PURITY STRESS-RELIEVED AND RECRYSTALLIZED MOLYBDENUM SHEET (0.062 INCH) AT 1800 and 2000 F[41]

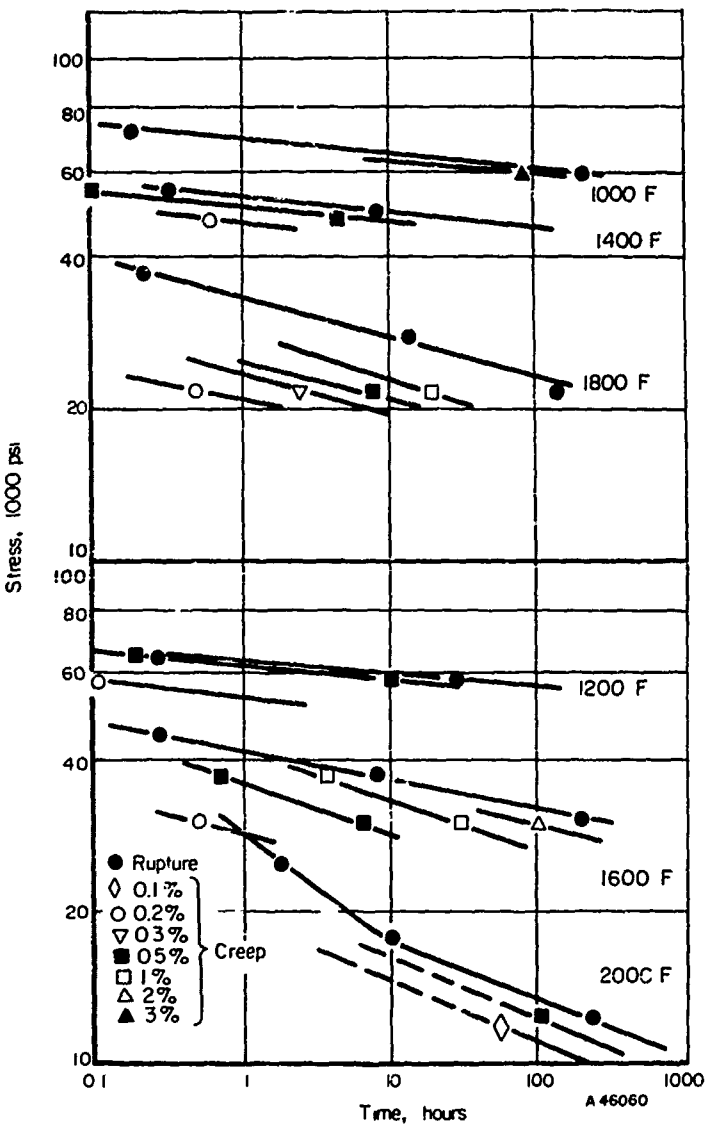


FIGURE A-36. CREEP AND RUPTURE CURVES FOR COMMERCIAL-PURITY ARC-CAST STRESS-RELIEVED MOLYBDENUM BAR (5/8-INCH DIAMETER) AT 1000 TO 2000 F[42]

0.015% carbon.

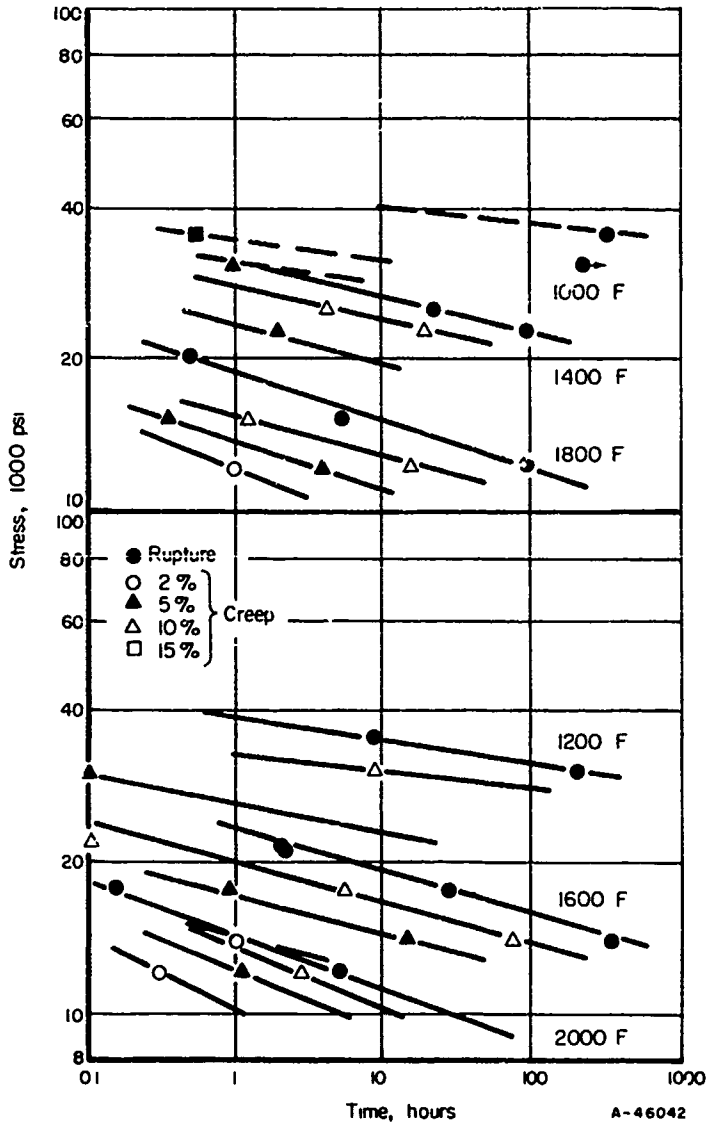


FIGURE A-37. CREEP AND RUPTURE CURVES FOR COMMERCIAL-PURITY ARC-CAST RECRYSTALLIZED MOLYBDENUM BAR (5/8-INCH DIAMETER) AT 1000 TO 2000 F[42]

0.015% carbon.

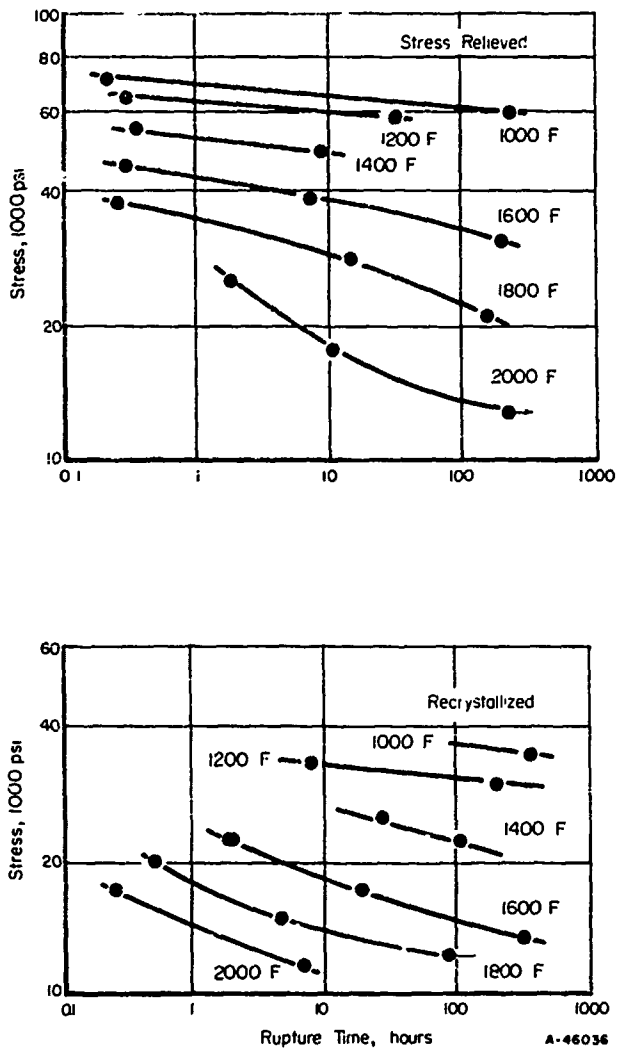


FIGURE A-38. RUPTURE CURVES FOR STRESS RELIEVED AND RECRYSTALLIZED MOLYBDENUM BAR (5/8-INCH DIAMETER) AT 1000 TO 2000 F[illegible]

Stress relieved 1 hour at 1800 F.
Recrystallized 1 hour at 2150 F.
0.015% carbon.

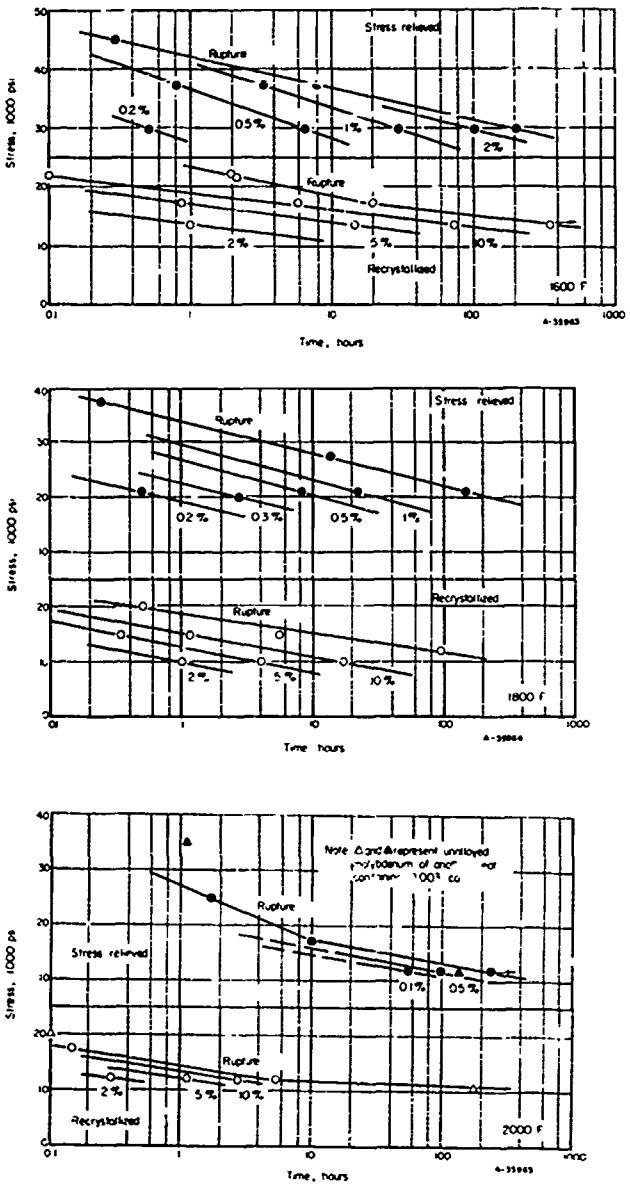


FIGURE A-39. CREEP AND RUPTURE CURVES FOR STRESS-RELIEVED AND RECRYSTALLIZED MOLYBDENUM AT 1600, 1800, AND 2000 F[43]

0.015% carbon.

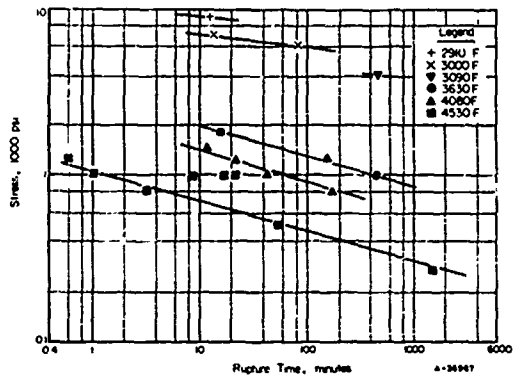


FIGURE A-40. RUPTURE CHARACTERISTICS OF POWDER-METALLURGY MOLYBDENUM AT 2910 TO 4930 F[44]

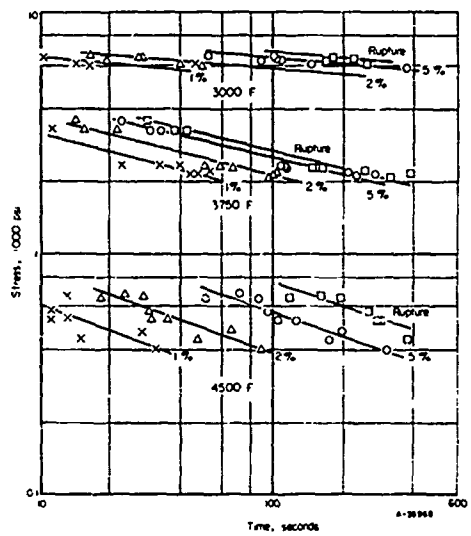


FIGURE A-41. HIGH-TEMPERATURE CREEP AND RUPTURE CURVES FOR ARC-CAST MOLYBDENUM SHEET (0.060 INCH) IN ARGON[34]

Specimens were loaded at room temperature and heated rapidly to test temperature. Creep measurements were made for maximum time of 5 minutes.

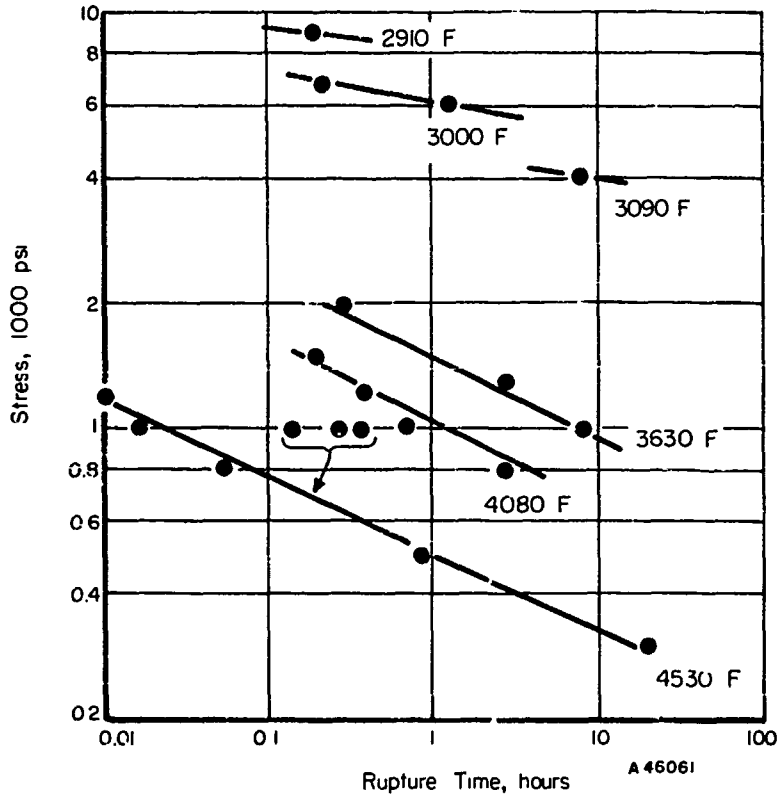


FIGURE A-42. HIGH-TEMPERATURE RUPTURE CURVES FOR COMMERCIAL-PURITY POWDER-METALLURGY MOLYBDENUM BAR (1/4-INCH DIAMETER) IN HELIUM[24]

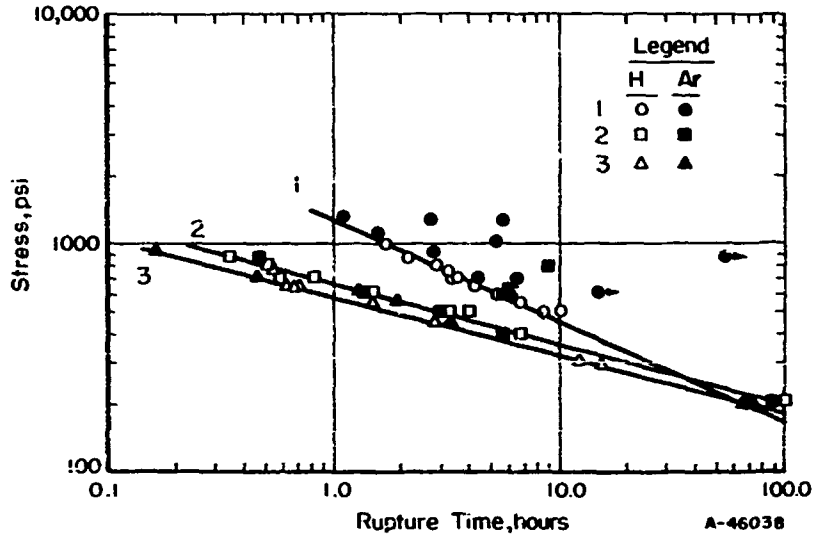


FIGURE A-43. STRESS-RUPTURE PROPERTIES OF AS-RECEIVED POWDER-METALLURGY AND ARC-CAST MOLYBDENUM SHEET (0.010 TO 0.020 INCH) IN HYDROGEN AND ARGON AT 3990 F[45]

Identification	Method of Consolidation	Analyses, ppm													
		C	O	N	H	Fe	W	Si	Mn	Cu	Ca	Al	Cr	V	Zr
1	PM	67	133	15	13	100	<400	<90	<100	<10	<50	<50	<50	<100	<50
2	AC	68	184	16	12	200	<400	<90	<100	<10	<50	<50	<50	<100	<50
3	AC	54	129	4	12	100	<400	100	<100	<10	<50	<50	<50	<100	<50

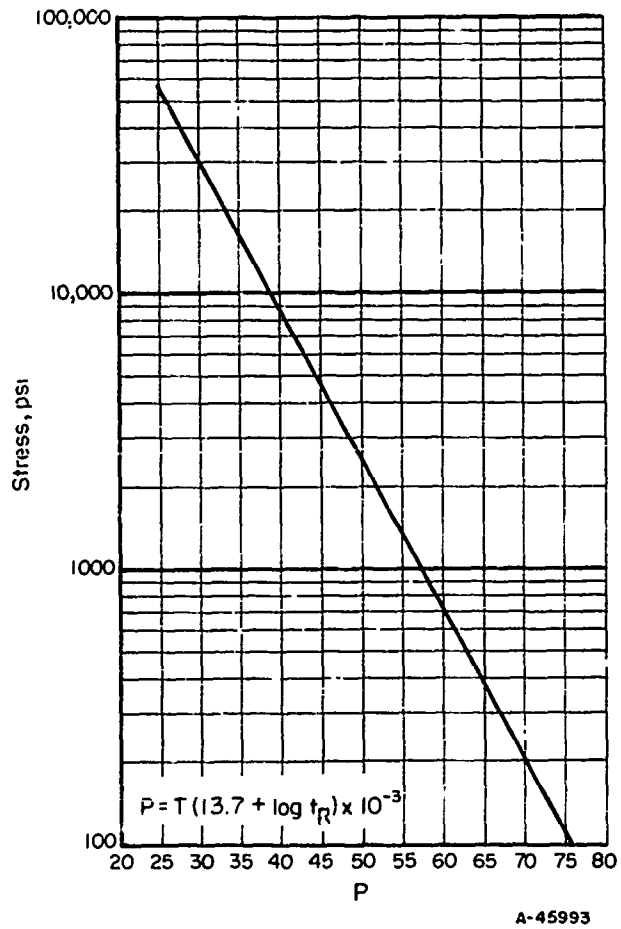


FIGURE A-44. LARSON-MILLER PARAMETER AS A FUNCTION OF STRESS FOR ARC-CAST MOLYBDENUM SHEET (0.010 TO 0.020 INCH)[45]

TABLE A-17. HARDNESS SPECIFICATION FOR WROUGHT AND RECRYSTALLIZED ARC-CAST MOLYBDENUM BARS[a][6]

Diameter, inches	Hardness, DPH[b] Minimum	Maximum
	Wrought	
Over 13/32 to 7/8	230	280
Over 7/8 to 1-1/8	225	270
Over 1-1/8 to 1-7/8	215	260
Over 1-7/8 to 2-7/8	210	250
Over 2-7/8 to 3-1/2	205	240
Over 3-1/2 to 4-1/2	200	230
	Recrystallized	
Over 13/32 to 4-1/2	--	200

(a) Hardness determined at mid-radius of bar.
(b) 10-kg load.

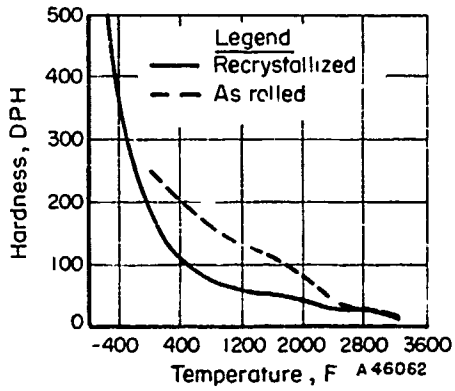


FIGURE A-45. EFFECT OF TEMPERATURE ON THE HARDNESS OF COMMERCIAL-PURITY ARC-CAST WROUGHT AND RECRYSTALLIZED MOLYBDENUM[24]

TABLE A-18. BEND DUCTILITY REQUIREMENTS FOR ARC-CAST MOLYBDENUM PLATE AND SHEET[a]

Direction of Bend Axis	Bend Radius Value, T	
	Maximum	Typical
	Plate, Up to 0.250 Inch[9]	
Parallel to rolling	3	1
Transverse to rolling	3	1
	Sheet[10]	
Parallel to rolling	2	0
Transverse to rolling	2	0

(a) 3/4 by 2-inch specimens. Moderate loading rate.

TABLE A-19. EFFECT OF TEMPERATURE ON THE COMPRESSIVE YIELD STRENGTH OF ARC-CAST MOLYBDENUM BAR (3/4-INCH DIAMETER)[a][32]

Temperature, F	Compressive Yield Strength (0.2% Offset), 1000 psi
RT	104.0
400	76.2
600	73.0
800	70.4
1000	68.5
1200	66.8
1400	59.6
1600	58.6
1800	54.0
2000	46.8
2200	10.9
2400	5.65

(a) Tested in argon at 0.05 inch per minute crosshead speed.

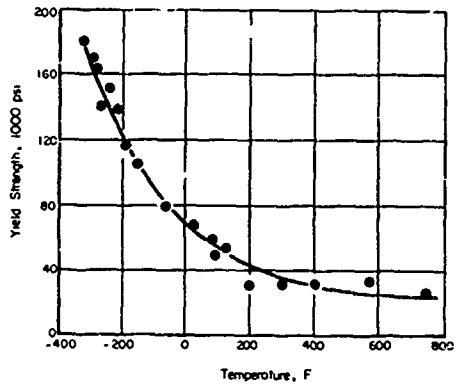


FIGURE A-46. EFFECT OF TEMPERATURE ON THE COMPRESSIVE YIELD STRENGTH OF RECRYSTALLIZED COMMERCIAL-PURITY POWDER-METALLURGY MOLYBDENUM BAR (0.200-INCH DIAMETER)[24]

Recrystallized 1/2 hour at 2280 F.
Test rate 2.8×10^{-4} per second.

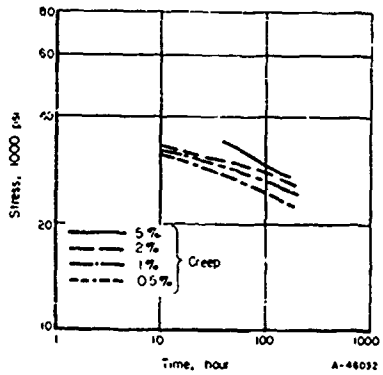


FIGURE A-47. STATIC COMPRESSION CREEP CURVES FOR COMMERCIAL-PURITY ARC-CAST SWAGED MOLYBDENUM BAR (0.250-INCH DIAMETER) AT 1600 F[24]

TABLE A-20. EFFECT OF TEMPERATURE ON THE SHEAR STRENGTH OF ARC-CAST MOLYBDENUM SHEET[36]

Temperature, F	Shear Strength, 1000 psi	
	0.015-Inch Sheet	0.060-Inch Sheet
-100	107	--
-50	84	--
0	89	75, 78
32	84	69, 75
75	83	79
200	64, 68	63, 65
400	57	52
600	54	49
800	50	45
1000	50	45
1200	46	42
1400	44	35
1600	39	32
1800	36	26

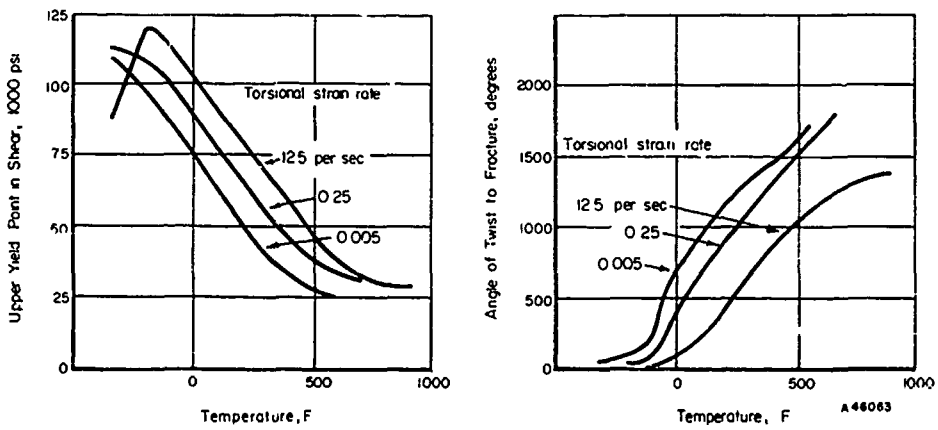
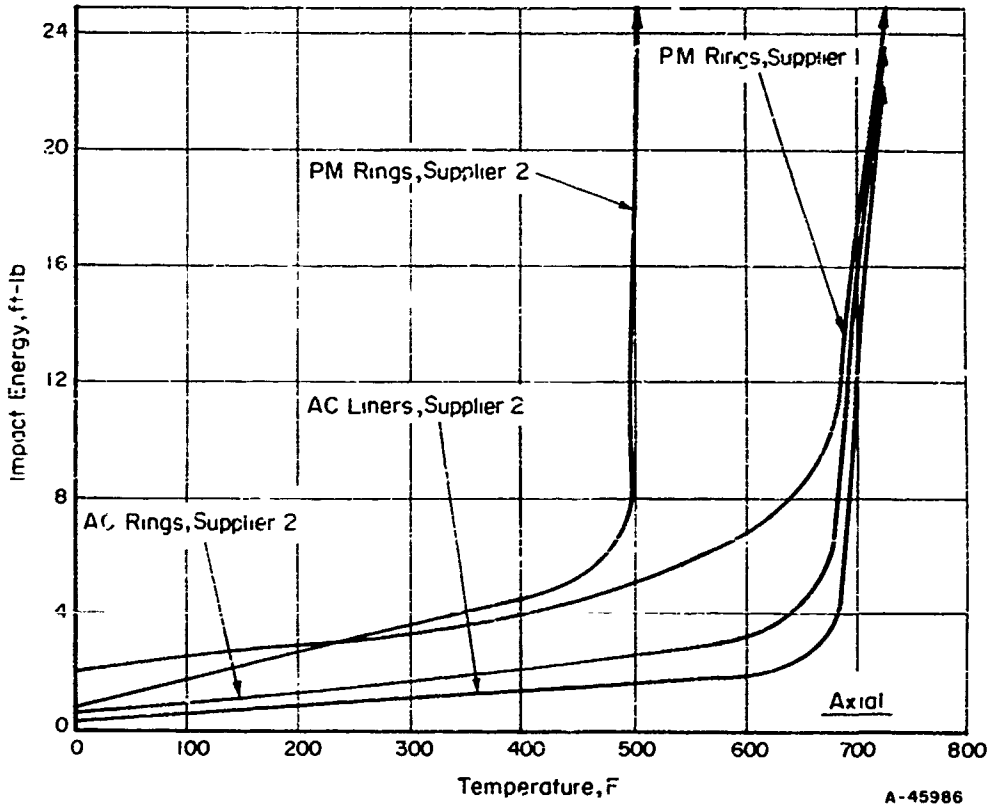


FIGURE A-48. EFFECT OF TEMPERATURE ON THE SHEAR PROPERTIES OF MOLYBDENUM[13]



Element	Analyses, weight per cent			
	PM Ring, Supplier 1	PM Ring, Supplier 2	AC Ring, Supplier 2	AC Liner, Supplier 2
C	--	0.006	0.020-0.028	0.015
Si	0.020	0.001	0.003-0.004	0.002
Ni	<0.001	0.001	0.001	0.001
Fe	0.003	0.003	0.001-0.002	0.002
Mn	<0.001	0.001	--	--
Mg	<0.001	0.001	--	--
Cr	<0.001	0.001	--	--
W	0.005	0.003	--	--
Sn	0.002	0.001	--	--
Cu	0.001	0.001	--	--
Ca	<0.001	0.001	--	.
Al	0.001	0.001	--	--
O	--	0.0022	0.0003-0.0007	0.0002
H	--	0.0006	0.00001-0.00003	0.001
N	--	0.0006	0.0001-0.0004	0.0001

FIGURE A-49. EFFECT OF TEMPERATURE ON THE IMPACT STRENGTH (CHARPY V-NOTCH) OF POWDER-METALLURGY AND ARC-CAST SECTIONS TAKEN FROM MOLYBDENUM FORGINGS[31]

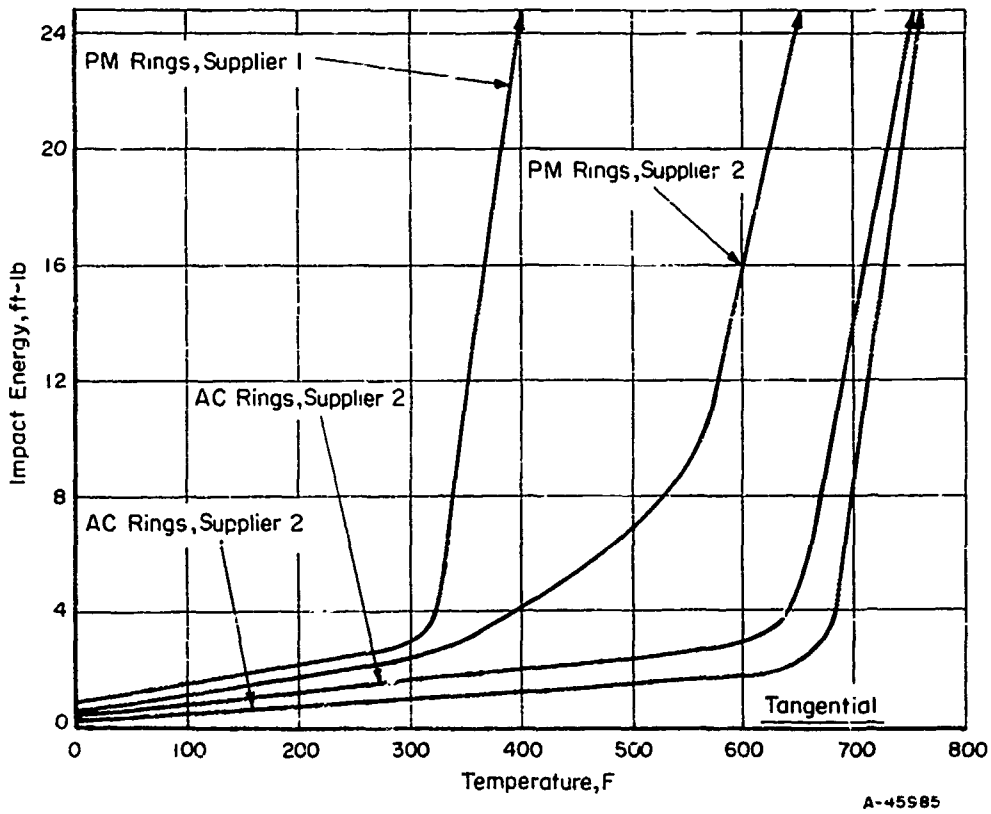


FIGURE A-49. (CONTINUED)

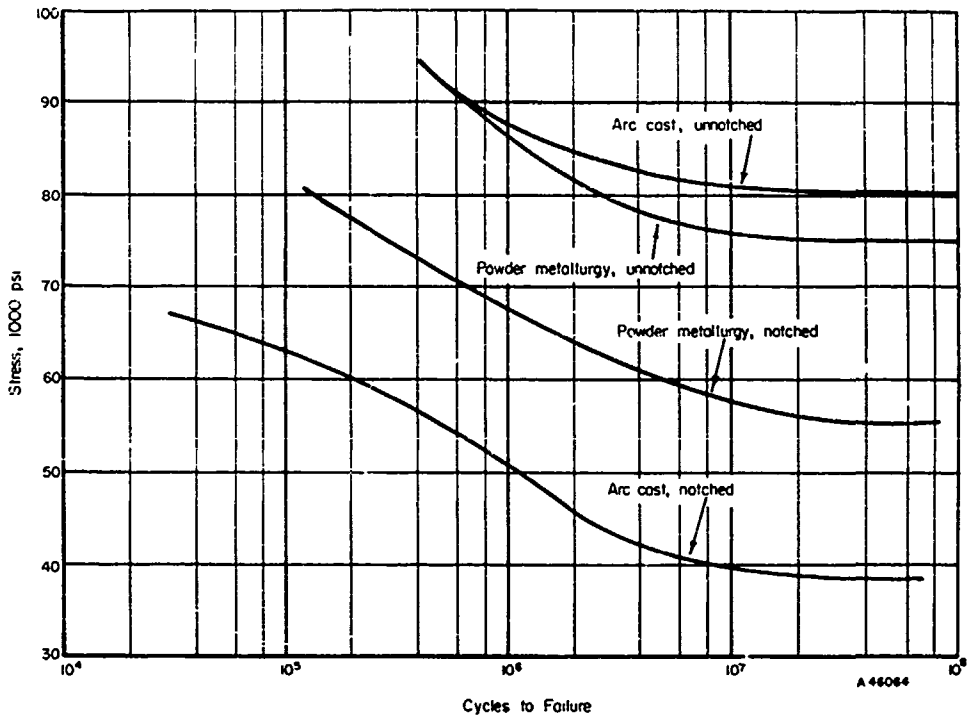


FIGURE A-50. FATIGUE PROPERTIES OF UNNOTCHED AND NOTCHED ARC-CAST AND POWDER-METALLURGY MOLYBDENUM[46]

	Carbon Content, weight per cent
Arc cast	0.04
Powder metallurgy	0.02

R. R. Moore rotating-beam machine, 10,000 rpm.
Minimum-section diameter, 0.260 inch.

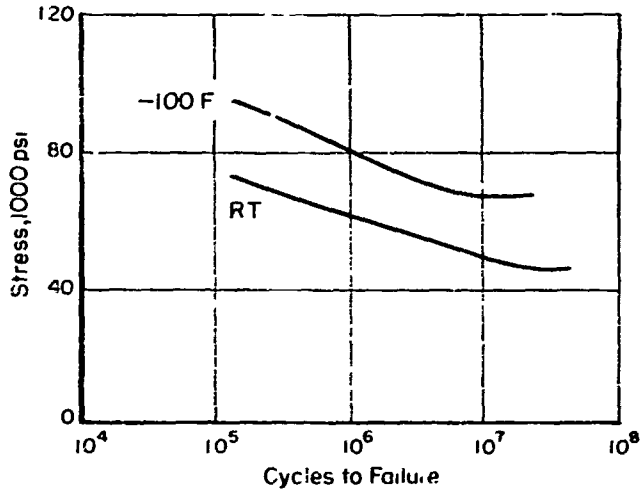


FIGURE A-51. LOW-TEMPERATURE FATIGUE PROPERTIES OF POWDER-METALLURGY MOLYBDENUM SHEET (0.025 INCH)[24]

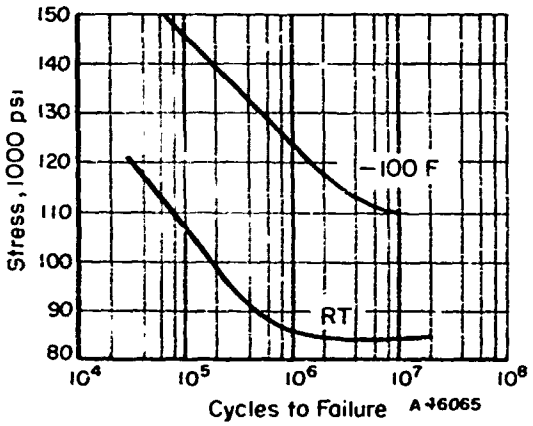


FIGURE A-52. LOW-TEMPERATURE FATIGUE PROPERTIES OF POWDER-METALLURBY MOLYBDENUM WIRE (0.004-INCH DIAMETER)[47]

Wire was annealed to a room-temperature tensile strength of 111,000 psi.

4. Metallurgical Properties

a. Fabricability: initial breakdown of as-cast ingots is usually done by extrusion; forging is conducted at 2150 to 2350 F maximum, finishing temperature 1500 to 1700 F minimum; for optimum properties, forging and reheating temperatures must be controlled to produce at least 50 per cent reduction by warm work below the recrystallization temperature, as each successive operation is performed, the heating temperature must be lowered; reductions of up to 90 per cent are possible without an intermediate recrystallization anneal[40]; recommended work temperatures after extrusion are illustrated in Figures A-53 and A-54

b. Transition temperature: Tables A-21 and A-22
Figures A-55 through A-60

c. Weldability: can be welded to itself or to any material with which it readily alloys by arc, electrical resistance, percussion, flash or electron-beam techniques; properly welded arc-cast molybdenum has a ductility at room temperature satisfactory for assembly and forming, but at slightly elevated temperatures (200 to 400 F), the ductility is better, molybdenum prepared by powder-metallurgy techniques does not behave as satisfactorily[24]

d. Stress-relief temperature: 1600 to 1800 F[13]

e. Recrystallization temperature: Figures A-61 through A-69

TABLE A-21. EFFECT OF HEAT TREATMENT ON THE TRANSITION TEMPERATURE AND NOTCH SENSITIVITY OF MOLYBDENUM BAR[38]

Condition	Ductility Transition Temperature, C		Difference Between Notch and Unnotched Ductility Transition Temperature, Δ C
	Unnotched	Notched ($K_t \approx 3$)	
As wrought (25%)	75	200	125
As wrought (68%)	-25	175	200
Low temp, stress relieved	-50	150	200
High temp, stress relieved	-50	125	175
Recrystallized (small grain)	50	200	150
Recrystallized (medium grain)	200	325	125
Recrystallized (large grain)	225	325	100

TABLE A-22. BEND-TRANSITION TEMPERATURE REQUIREMENTS FOR ARC-CAST MOLYBDENUM PLATE AND SHEET[a]

Direction of Bend Axis	Bend-Transition Temperature, F	
	Maximum	Typical
Plate, Up to 0.250 Inch[9]		
Parallel to rolling	300	70
Transverse to rolling	300	70
Sheet[10]		
Parallel to rolling	100	65
Transverse to rolling	100	65

(a) Bend-transition temperature is defined as the minimum temperature at which a specimen will bend through 105 degrees with a moderate variable loading rate over a 1T radius without failing.

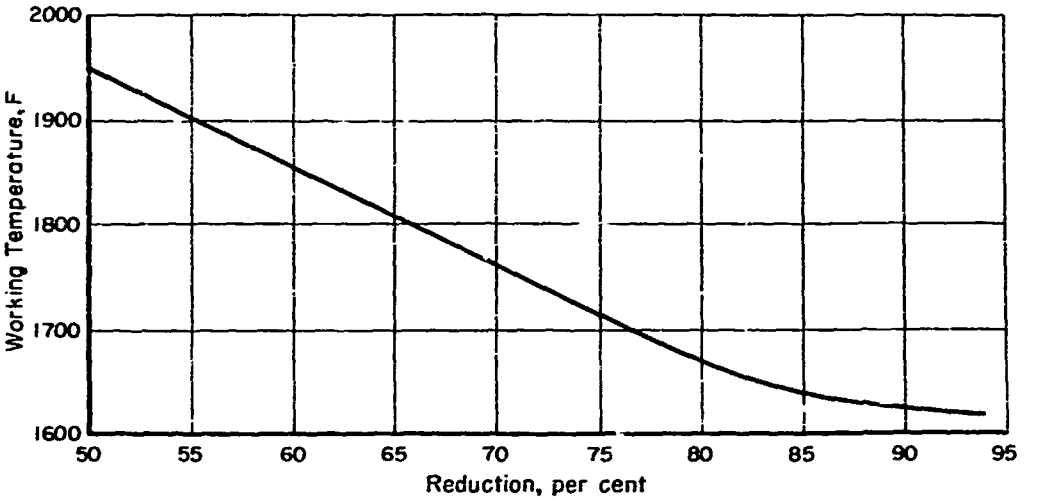


FIGURE A-53. APPROXIMATE RECOMMENDED WORKING TEMPERATURES FOR CORRESPONDING AMOUNTS OF HOT-COLD WORK FOR ARC-CAST MOLYBDENUM[49]

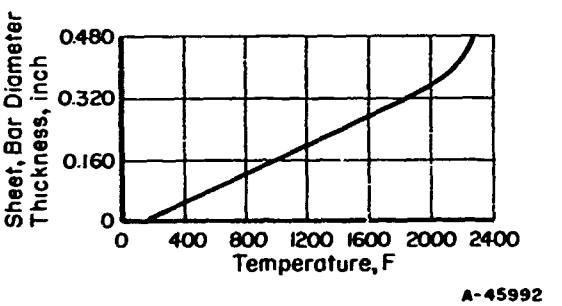


FIGURE A-54. RECOMMENDED WORKING TEMPERATURE FOR COMMERCIAL-PURITY MOLYBDENUM BAR AND SHEET[24]

Applies to spinning, shearing, stamping, punching, hydroforming, bending, stretch forming, and deep drawing.

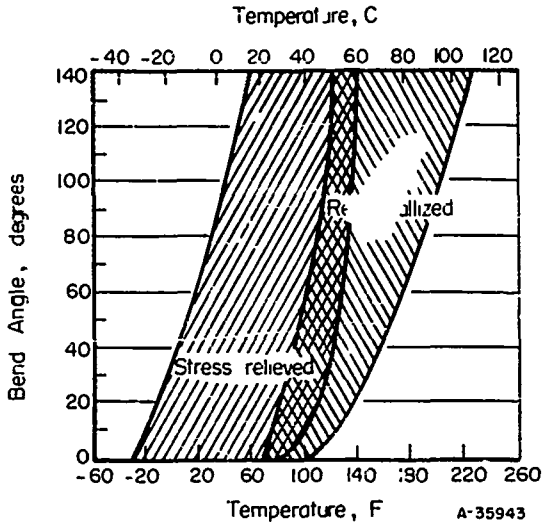


FIGURE A-55. EFFECT OF PRIOR PROCESSING ON THE BEND-TRANSITION TEMPERATURE OF ARC-CAST MOLYBDENUM SHEET (1/16 INCH)[24]

Specimens 1/2 by 1 inch.

Test rate 19 inches per minute.

Bend radius 1T.

Data for seven sheets.

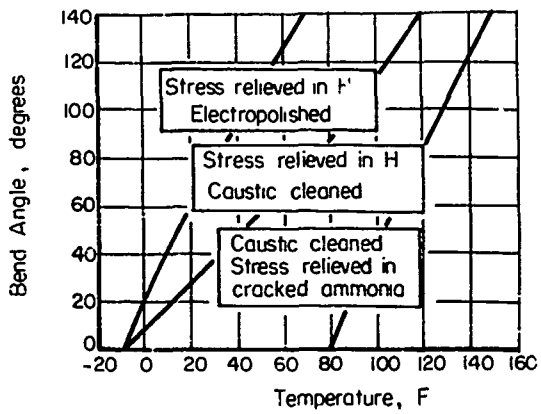


FIGURE A-56. BEND-TRANSITION TEMPERATURES FOR ARC-CAST MOLYBDENUM SHEET (1/16 INCH) SUBJECTED TO INDICATED THERMAL AND SURFACE TREATMENTS[20]

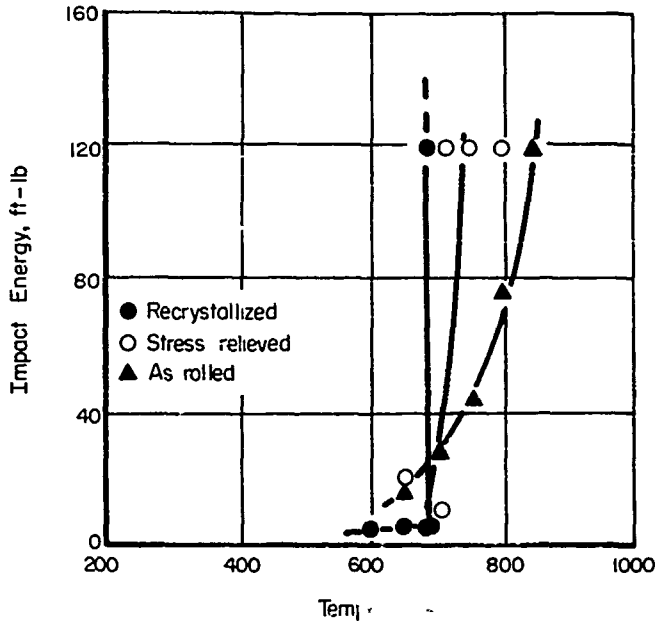


FIGURE A-57. IMPACT (CHARPY V-NOTCH) TRANSITION BEHAVIOR OF COMMERCIAL-PURITY ARC-CAST MOLYBDENUM[24]

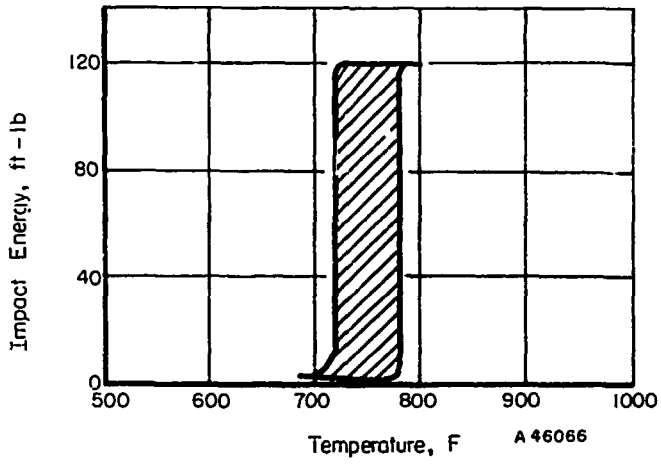


FIGURE A-58. TYPICAL IMPACT (CHARPY V-NOTCH) TRANSITION RANGE FOR MOLYBDENUM[50]

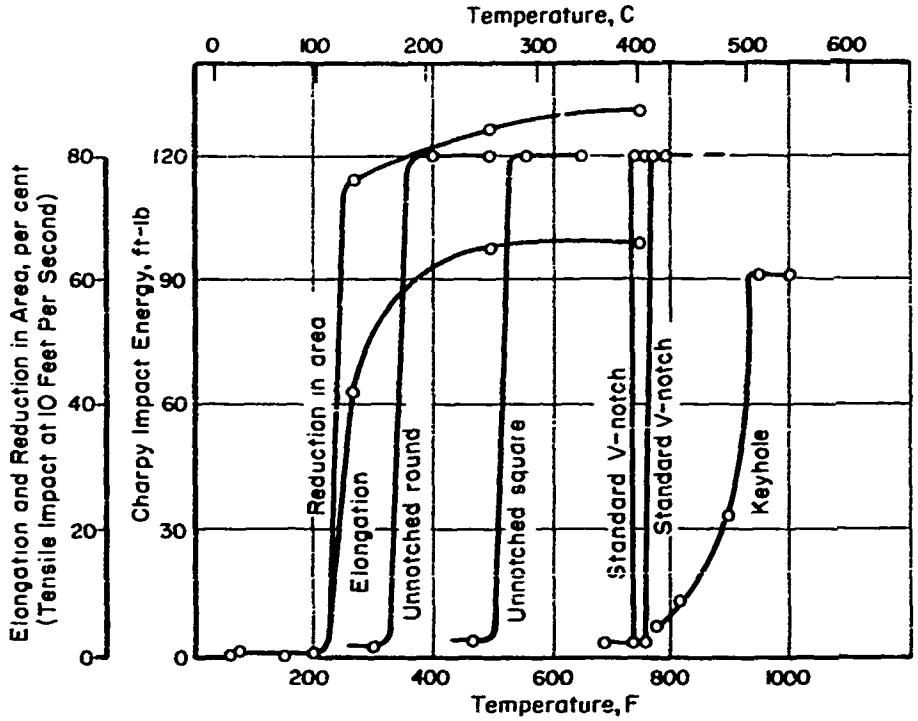


FIGURE A-59. EFFECT OF TYPE OF STRESS SYSTEM ON THE TRANSITION TEMPERATURE OF RECRYSTALLIZED MOLYBDENUM[51]

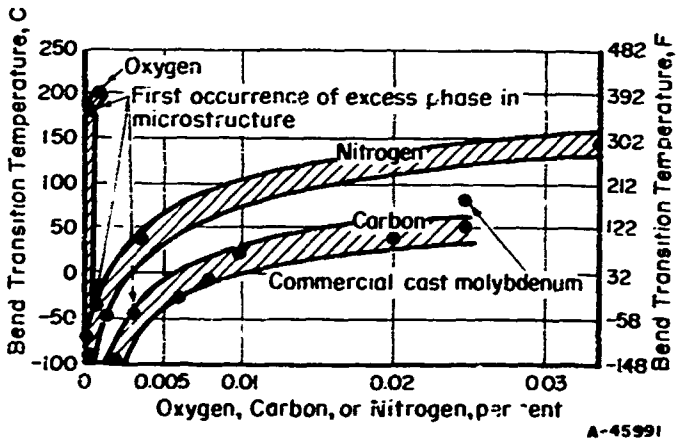


FIGURE A-60. EFFECT OF OXYGEN, CARBON, AND NITROGEN ON THE BEND-TRANSITION TEMPERATURE OF MOLYBDENUM[52]

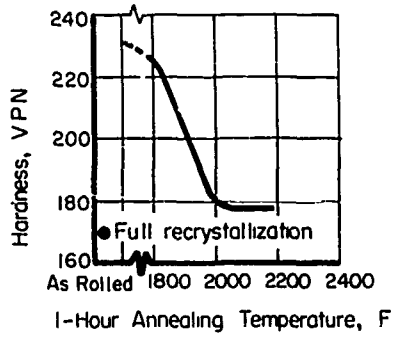


FIGURE A-61. EFFECT OF ANNEALING TEMPERATURE ON THE HARDNESS OF COMMERCIAL-PURITY MOLYBDENUM BAR (1-1/16 INCH SQUARE)[53]

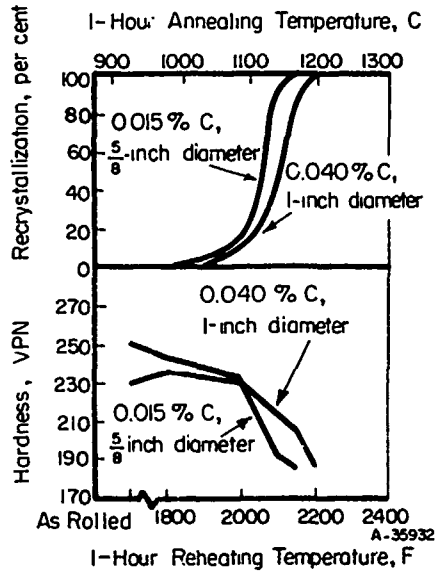
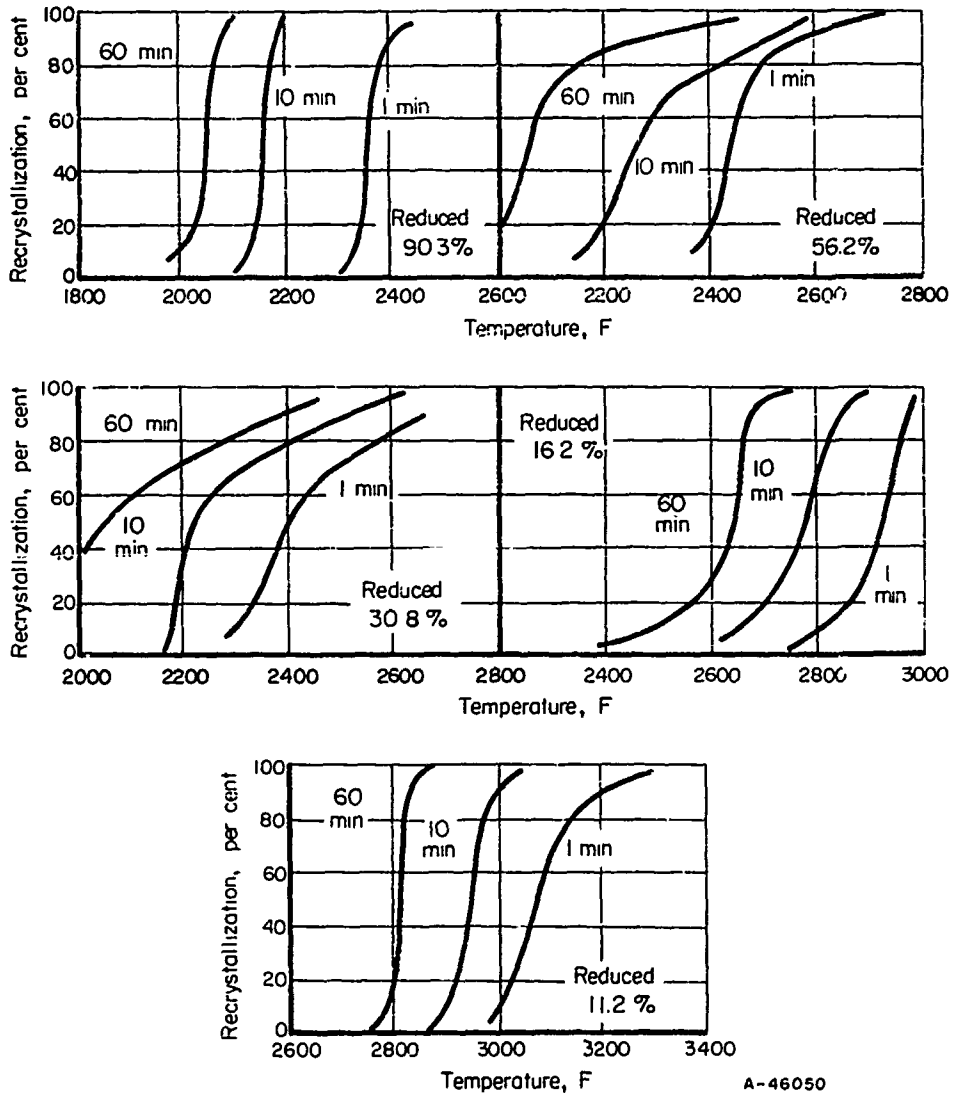


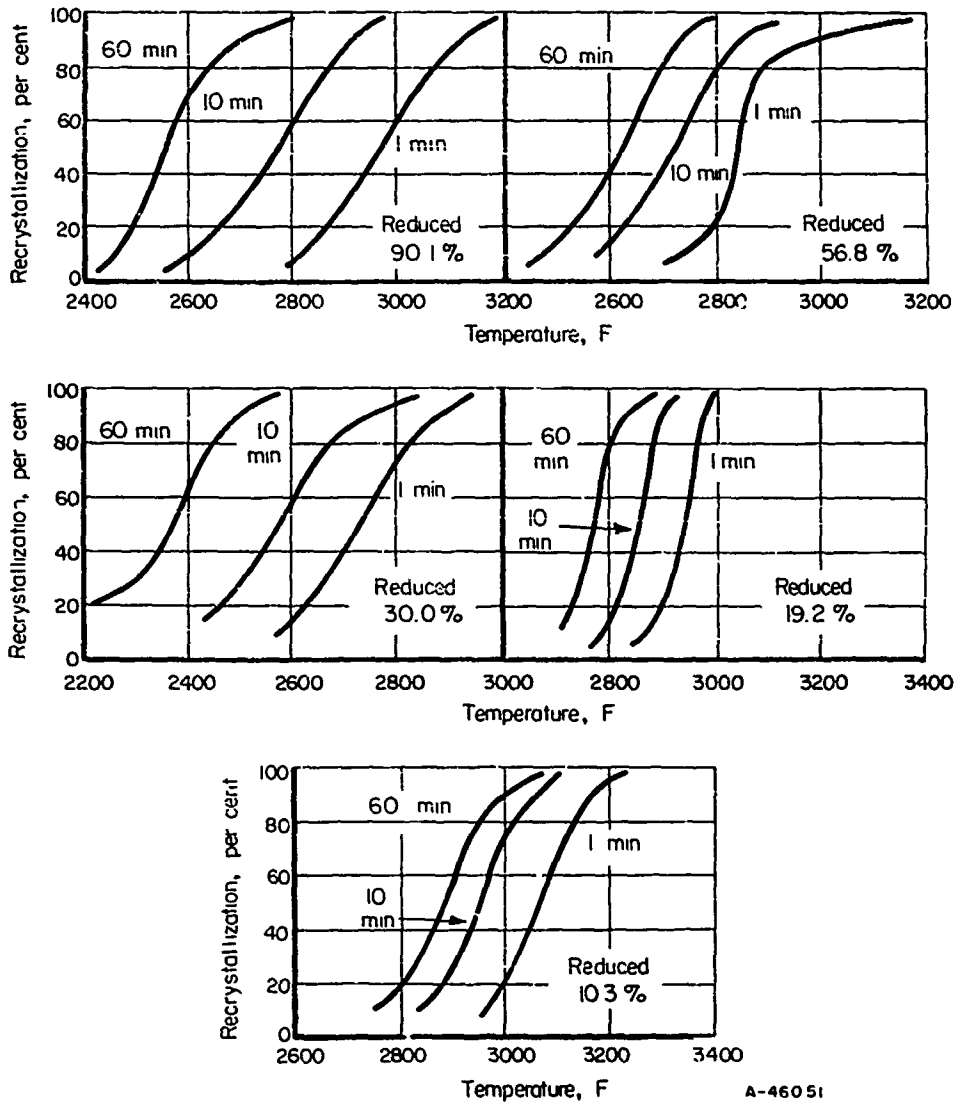
FIGURE A-62. EFFECT OF REHEATING TEMPERATURE ON THE RECRYSTALLIZATION AND ROOM-TEMPERATURE HARDNESS OF AS-ROLLED MOLYBDENUM BAR[24]



a. Rolled at 2200 F

FIGURE A-63. RECRYSTALLIZATION BEHAVIOR AS A FUNCTION OF TIME AND TEMPERATURE FOR MOLYBDENUM BARS ROLLED TO INDICATED REDUCTIONS[54]

0.008% carbon.



b Rolled at 3000 F

FIGURE A-63. (CONTINUED)

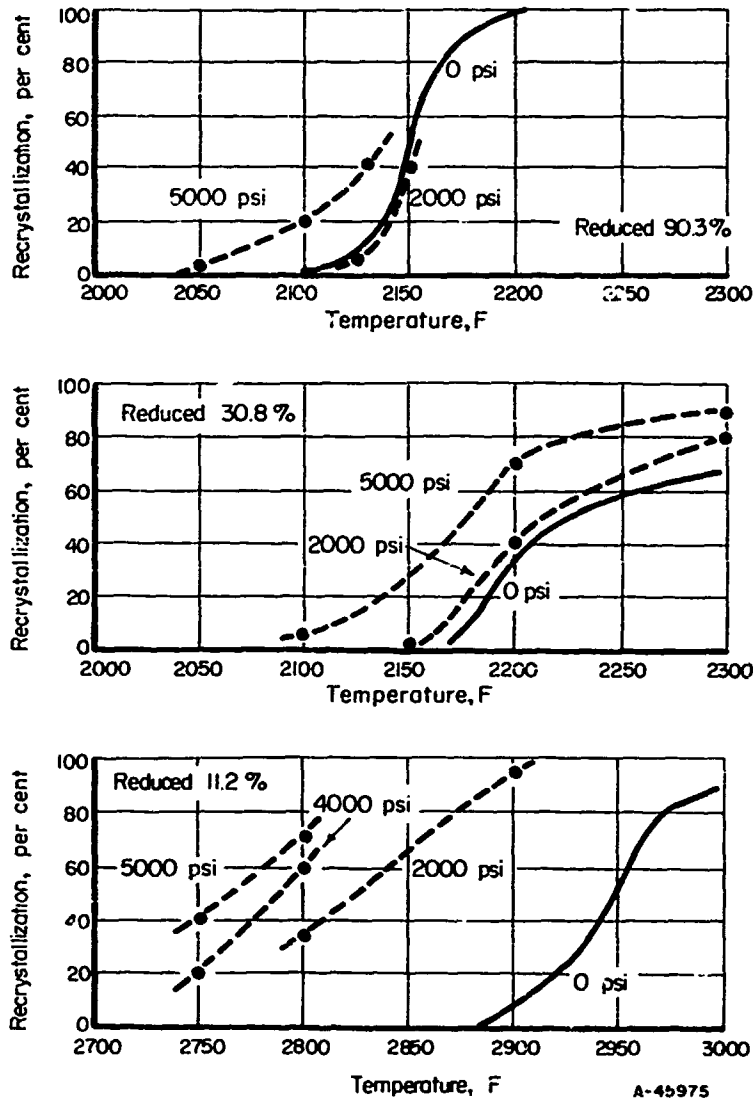


FIGURE A-64. RECRYSTALLIZATION BEHAVIOR AS A FUNCTION OF TEMPERATURE AND EXTERNALLY APPLIED STRESS FOR MOLYBDENUM BARS(54)

Annealed for 10-minute periods. Subjected to indicated reductions at 2200 F. 0.008% carbon.

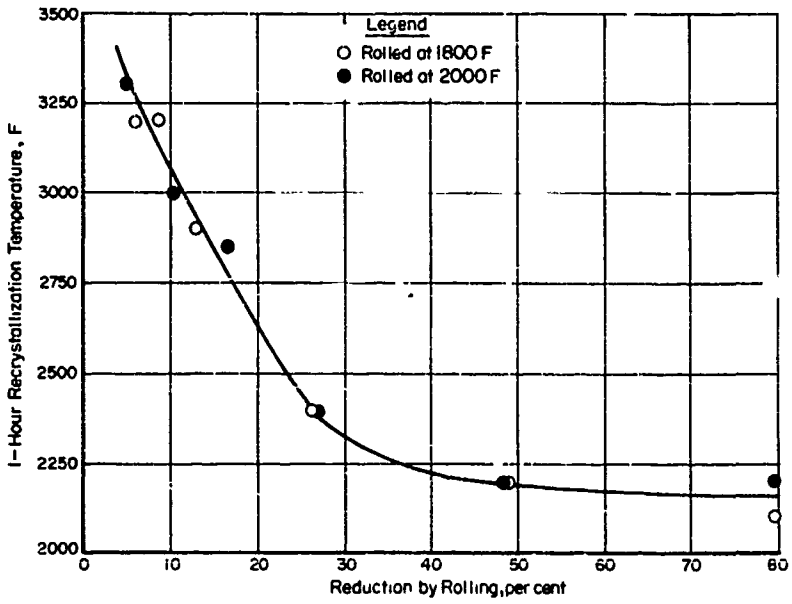


FIGURE A-65. TEMPERATURE FOR COMPLETE RECRYSTALLIZATION VERSUS PER CENT REDUCTION FOR MOLYBDENUM BAR (1/2 INCH SQUARE)[25]

0.025% carbon.

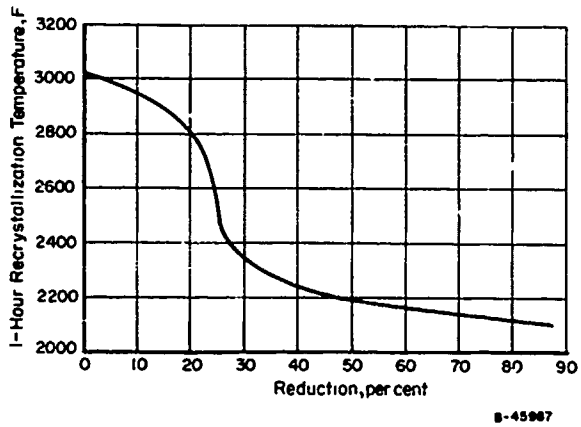


FIGURE A-66. EFFECT OF DEFORMATION ON THE MINIMUM TEMPERATURE FOR COMPLETE RECRYSTALLIZATION OF ARC-CAST MOLYBDENUM[49]

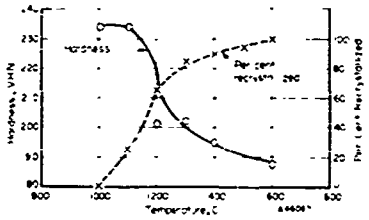


FIGURE A-67. ANNEALING CURVE FOR ARC-CAST MOLYBDENUM BAR[22]

1/4 hour at temperature, hydrogen atmosphere, air cooled.

Arc-melted ingot swaged to 7/16-inch diameter bar
Working temperatures generally above 600 C.

Element	Weight Per Cent
C	0.002
O	0.0022
N	0.001
H	0.00006
Ta	<0.2
W	<0.1
Others	<0.05

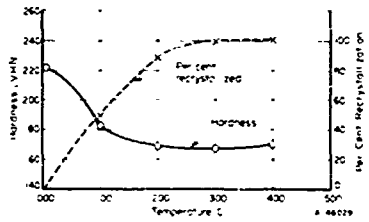


FIGURE A-68. ANNEALING CURVE FOR ARC-CAST MOLYBDENUM SHEET[22]

1/4 hour at temperature, hydrogen atmosphere, air cooled.

Arc-melted ingot rolled to 0.065-inch sheet. Working temperatures generally above 600 C.

Element	Weight Per Cent
C	0.026
O	0.0009
N	<0.001
H	0.00006
Ta	<0.2
W	<0.1
Others	<0.05

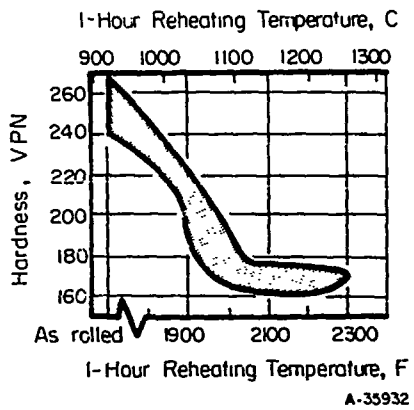


FIGURE A-69. RECRYSTALLIZATION BEHAVIOR OF ARC-CAST MOLYBDENUM SHEET (1/16 INCH) AS REFLECTED BY ROOM-TEMPERATURE HARDNESS[20]

Data for seven sheets. Analyses 0.0004% O, 0.00002% H, and 0.0007% N.

Processing Schedule

1. Arc-cast ingot machined into an extrusion blank
2. Extruded
3. Extruded billet conditioned and recrystallized
4. Forged or rolled to a 1 to 2-in.-thick sheet bar
5. Sheet bar conditioned and recrystallized
6. Rolled to 1/4 to 3/8-in.-thick plate
7. Recrystallized
8. Rolled to 1/16-in. sheet.

References

(1) Proposed Tentative Specification for Molybdenum and Molybdenum-Alloy Forgings, American Society for Testing and Materials, ASTM Designation: B-62T (1962).

(2) Proposed Tentative Specification for Molybdenum and Molybdenum-Alloy Billets for Reforging, American Society for Testing and Materials, ASTM Designation: B-62T (1962).

(3) Proposed Tentative Specification for Molybdenum and Molybdenum Alloy Strip, Sheet, Foil, and Plate, American Society for Testing and Materials, ASTM Designation: B-62T (1962).

(4) Proposed Tentative Specification for Molybdenum and Molybdenum-Alloy Bar, Rod, and Wire, American Society for Testing and Materials, ASTM Designation: B-62T (1962).

(5) "Specification for Climelt Molybdenum Forging Billets", Climax Molybdenum Co., Number CMX-FB-5 (October, 1962).

(6) "Specification for Climelt Molybdenum Wrought Bars", Climax Molybdenum Co., Number CMX-WB-1 (May, 1961).

(7) "Unalloyed Molybdenum Billets", Universal-Cyclopes Steel Corp., Specification No. MFB-61-2 (March 20, 1961).

(8) "Unalloyed Molybdenum Bar", Universal-Cyclops Steel Corp., Specification No. MB-61-3 (April 12, 1961).

(9) "Unalloyed Molybdenum Plate", Universal-Cyclops Steel Corp., Specification No. MP-61-3 (April 12, 1961).

(10) "Unalloyed Molybdenum Sheet", Universal-Cyclops Steel Corp., Specification No. MS-61-3 (April 12, 1961).

(11) "Pressed and Sintered Molybdenum Billets, Slabs and Rings", Sylvania Electric Products, Inc., Technical Information Bulletin (May, 1962).

(12) "Unalloyed Molybdenum Refractory Metal, Sheet, Plate, Bar – Sintered or Arc Cast", Westinghouse Electric Corp., Special Technical Data 52-362 (June, 1962).

(13) Metals Handbook, Properties and Selection of Metals, 8th Edition, American Society for Metals, Cleveland, Ohio (1961), Vol 1, pp 1215-17

(14) Goldsmith, A., and Waterman, T. E., "Thermophysical Properties of Solid Materials", Armour Research Foundation, WADC TR 58-476 (October, 1958).

(15) Technical Bulletin No. 2, Universal-Cyclops Steel Corp. (1960).

(16) Sylvania Electric Products Inc., Data Sheet.

(17) Worthing, A. G., "Physical Properties of Well Seasoned Molybdenum and Tantalum as a Function of Temperature, "Phys. Rev., 28, 190 (1926).

(18) Taylor, R. E., and Finch, R. A., "The Specific Heats and Resistivities of Molybdenum, Tantalum, and Rhenium From Low to Very High Temperatures", Atomics International, Contract AT (11-1)-GEN-8, NAA-SR-6034 (September 15, 1961).

(19) Private communication from G. D. McArdle. Climax Molybdenum Co. (1963).

(20) Semchyshen, M., and Barr, R. Q., "Mechanical Properties of Molybdenum and Molybdenum-Base Alloy Sheet", ASTM STP No. 272 (1959).

(21) "Molybdenum and Molybdenum Alloy Tubing", Superior Tube Co., Data Memorandum No. 12, Sheet No. 1 (April 1962).

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

(23) Barr, R. Q., and Semchyshen, M., "Stress-Strain Curves for Wrought Molybdenum and Three Molybdenum-Base Alloys", Climax Molybdenum Co. (December, 1959).

(24) Molybdenum Metal, Climax Molybdenum Co. (1960).

(25) Semchyshen, M., and Barr, R. Q., "Arc-Cast Molybdenum-Base Alloys". Climax Molybdenum Co., Contract No. N9onr-82100 (1955).

(26) Pugh, J. W., "The Tensile Properties of Molybdenum at Elevated Temperatures", Transactions of the American Society for Metals, 47, 984 (1955).

(27) The Metal Molybdenum, Edited by J. J. Harwood, American Society for Metals, Cleveland, Ohio (1956), "Effects of Oxygen, Nitrogen, and Carbon on the Ductility of Wrought Molybdenum" (H. S. Spacil and J. Wulff), p 267.

(28) Northcott, L., Molybdenum, Metallurgy of the Rarer Metals No. 5, Butterworths Scientific Publications, London (1956).

(29) Barr, R. Q., Semchyshen, M., and Timmons, G. A., "Room-Temperature Creep Rate of Molybdenum and Effect of Strain Rate on the Tensile Properties of Molybdenum", Climax Molybdenum Co.

(30) Molybdenum, Metallwerke Plansee, Reutte, Tyrol, Austria.

(31) Warga, J. J., "Evaluation of Arc-Cast and Pressed and Sintered Unalloyed Molybdenum Forgings", Aerojet General Corp., Contract No. AF 33(657)-8890, Task No. 736103, Phase I (January 15, 1963).

(32) "Short-Time Compressive Properties of Molybdenum and Mo-0.5% Ti Alloy Bar", Universal Cyclops Steel Corp., Technical Bulletin No. 2.1.3.

(33) Brock, G. W. and Sinclair, G. M., "Elevated Temperature Tensile and Fatigue Behavior of Unalloyed Arc-Cast Molybdenum", WADC TN 59-59 (February, 1959).

(34) Preston, J. B., Roe, W. P., and Kattus, J. R., "Determination of the Mechanical Properties of Aircraft Structural Materials at Very High Temperatures After Rapid Heating", Southern Research Institute WADC TR 52-649, Part 1 (January, 1958).

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

(36) "Arc-Cast Molybdenum and Its Alloys, Mechanical and Elevated-Temperature Properties", Universal-Cyclops Steel Corp.

(37) Fabrication of Molybdenum, American Society for Metals, Cleveland, Ohio (1959), "Fabrication of Electronic Tube Components" (R. W. Yancey), pp 205-213.

(38) "Further Investigation of Notch Sensitivity of Refractory Metals", Battelle Memorial Institute, ASD-TDR-62-1004 (December, 1962)

(39) Warga, J. J., "An Investigation of the Elevated-Temperature Creep-Rupture Properties of Unalloyed Molybdenum Forgings Produced From Arc-Cast and Pressed and Sintered Materials", Aerojet General Corp., Contract No. AF 33(657)-8890, Task No. 738103, Phase I (January 15, 1963).

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

(41) "High Temperature Metals", Universal Cyclops Steel Corp. (October 28, 1957).

(42) Barr, R. Q., "Creep Rupture Data on Unalloyed Molybdenum from 1000 to 2000 F", Climax Molybdenum Co., Research Project 22, Metallurgy of Molybdenum Base Alloys, Assignment No. 1957-5 (December 3, 1958).

(43) Semchyshen, M., McArdle, G. D., and Barr, R. Q., "Development of High Strengths and High Recrystallization Temperatures in Molybdenum-Base Alloys", Climax Molybdenum Co., WADC TR 58-551 (February, 1959).

(44) Green, W. V., Smith, M. C., and Olson, D. M., "Short-Time Creep-Rupture Behavior of Molybdenum at High Temperatures", Transactions of the American Institute of Metallurgical Engineers, 215, 1061 (1959).

(45) Conway, J. B., et al., "Effect of Test Atmosphere on Stress-Rupture and Creep Properties of Molybdenum at 2200 C", General Electric Co., TM 63-6-3 paper presented at 9th Annual ANS Meeting, Salt Lake City (June, 1963).

(46) "Fatigue Properties of Molybdenum", Universal Cyclops Steel Corp., Technical Bulletin 2.1.2.

(47) Gala, T., Lepowski, W. J., and Gade, H. M., "How 7 Nonferrous Metals Perform at Low Temperatures", Materials and Methods, 44 (3), 116 (September, 1956).

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

(49) "Forging of Vacuum Arc-Cast Molybdenum, Mo + 0.5% Ti and Mo + 0.5% Ti-0.1% Zr (TZM)", Universal Cyclops Steel Corp., Technical Bulletin No. 2.5.3 (September 25, 1962).

(50) Technical Bulletin No. 2.1.1, Universal Cyclops Steel Corp.

(51) Arc-Cast Molybdenum and Its Alloys, Climax Molybdenum Co. (1955).

(52) Olds, L. E., Rengstorff, G. W. P. "Effects of Oxygen, Nitrogen, and Carbon on the Ductility of Cast Molybdenum," Jour. Met., 8 (1), 150 (February, 1956).

(53) Semchyshen, M., Barr, R. Q. and McArdle, G. D., "Effect of Thermal-Mechanical Variables on the Properties of Molybdenum Alloys", Climax Molybdenum Co., WADD TR 60-451 (November, 1960).

(54) Semchyshen, M., and Barr, R. Q., "Extrusion and Mechanical Properties of Some Molybdenum- and Tungsten-Base Alloys", Climax Molybdenum Co., ASD TR 61-193 (May, 1961).

Mo-1.5Cb

1. Identification of Material

   a. Chemical composition: Mo-1.5Cb

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

2. Physical Properties

   a. Density: 0.368 lb/in.^{3} (calculated)

3. Mechanical Properties

   a. Tensile Properties at Room Temperature

      Ultimate tensile strength: Table A-23

      Tensile yield strength: Table A-23

      Elongation: Table A-23

      Reduction in area: Table A-23

   b. Effect of Temperature on Tensile Properties

      Ultimate tensile strength: Table A-24
      Figures A-70 and A-71

      Tensile yield strength: Table A-24
      Figures A-70 and A-71

      Elongation: Table A-24
      Figures A-70 and A-71

      Reduction in area: Table A-24

   c. Creep and Stress-Rupture Properties

      Tables A-25 and A-26
      Figure A-72

   d. Other Selected Mechanical Properties

      Hardness: Figure A-73

      Bend ductility: Figures A-74 through A-76

TABLE A-23. ROOM-TEMPERATURE TENSILE PROPERTIES OF Mo-1.5Cb BAR AND SHEET

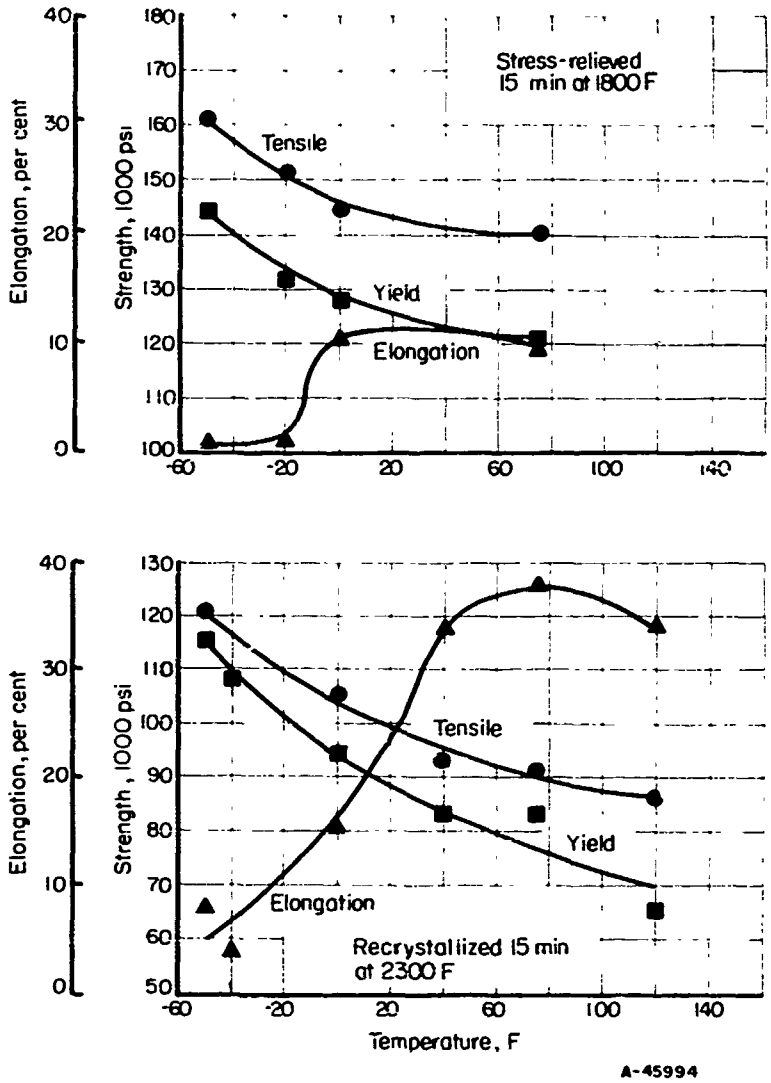
Composition (Balance Molybdenum) weight per cent	Condition	Tensile Strength, 1000 psi	Yield Strength 1000 psi	Elongation, per cent	Reduction in Area, per cent
	Bar (1/4-Inch Diameter)[1]				
1.41Cb-0.047C	As rolled	157.5	111.9	3	3.3
	Stress relieved, 1 hour 2100 F	127.8	107.9	4	2.5
	Recrystallized, 1 hour 2550 F	87.7	54.9	44	36.8
1.45Cb-0.25C	As rolled	165.5	121.4	2	1.6
	Stress relieved, 1 hour 2000 F	155.6	120.2	1	0.8
	Recrystallized, 1 hour 2700 F	102.7	67.9	14	11.4
	Sheet (0.050 Inch)[a][2]				
1.35Cb-0.028C[b]	Stress relieved, 1/4 hour 1800 F	140.6 (L)	120.9 (L)	10 (L)	--
		147.7 (T)	131.9 (T)	7 (T)	--
1.35Cb-0.028C[b]	Recrystallized, 1/4 hour 2300 F	91.7 (L)	83.7 (L)	38 (L)	--
		95.5 (T)	81.8 (T)	23 (T)	--
1.35Cb-0.028C[c]	Stress relieved, 1/4 hour 1800 F	135.3 (L)	111.3 (L)	10 (L)	--
		145.5 (T)	129.8 (T)	6 (T)	--
1.35Cb-0.028C[c]	Recrystallized, 1/4 hour 2300 F	92.7 (L)	81.7 (L)	29 (L)	--
		99.2 (T)	81.6 (T)	26 (T)	--

(a) Tests rate 0.005 inch per inch per minute in the elastic range, then 0.05 inch per inch per minute to fracture.
(b) Sheet rolled in air with a relatively low finishing temperature.
(c) Sheet rolled in air with a relatively high finishing temperature.

TABLE A-24. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF Mo-1.5Cb BAR AND SHEET

Composition (Balance Molybdenum), weight per cent	Condition	Temperature, F	Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation, per cent	Reduction in Area, per cent
		Bar (1/4-Inch Diameter)[1]				
1.41Cb-0.047C	Stress relieved, 1 hour 2100 F	1800	87.3	63.0	17	56.1
		2400	23.7	14.1	77	94.6
1.41Cb-0.047C	Recrystallized, 1 hour 2550 F	1800	41.0	20.2	25	35.4
		2400	21.6	11.8	31	37.9
1.45Cb-0.25C	As rolled	1800	99.6	62.4	20	55.3
1.45Cb-0.25C	Stress relieved, 1 hour 2000 F	1800	101.3	86.4	7	14.5
		2400	64.4	--	36	88.4
1.45Cb-0.25C	Recrystallized, 1 hour 2700 F	1800	45.4	19.9	40	81.1
		2400	30.5	--	71	93.3
		Sheet (0.050 Inch)[a][2]				
1.35Cb-0.028C[b]	Stress relieved, 1/4 hour 1800 F	2000	75.0	45.4	8	--
1.35Cb-0.028C[b]	Recrystallized, 1/4 hour 2300 F	2000	41.0	--	25.5	--
		2400	21.4	--	63.5	--
		3000	7.5	--	55.5	--
1.35Cb-0.028C[c]	Stress relieved, 1/4 hour 1800 F	2000	73.9	--	4	--
1.35Cb-0.028C[c]	Recrystallized, 1/4 hour 2300 F	2000	41.7	--	18.5	--
		2400	20.2	--	70	--
		3000	8.0	--	44.5	--

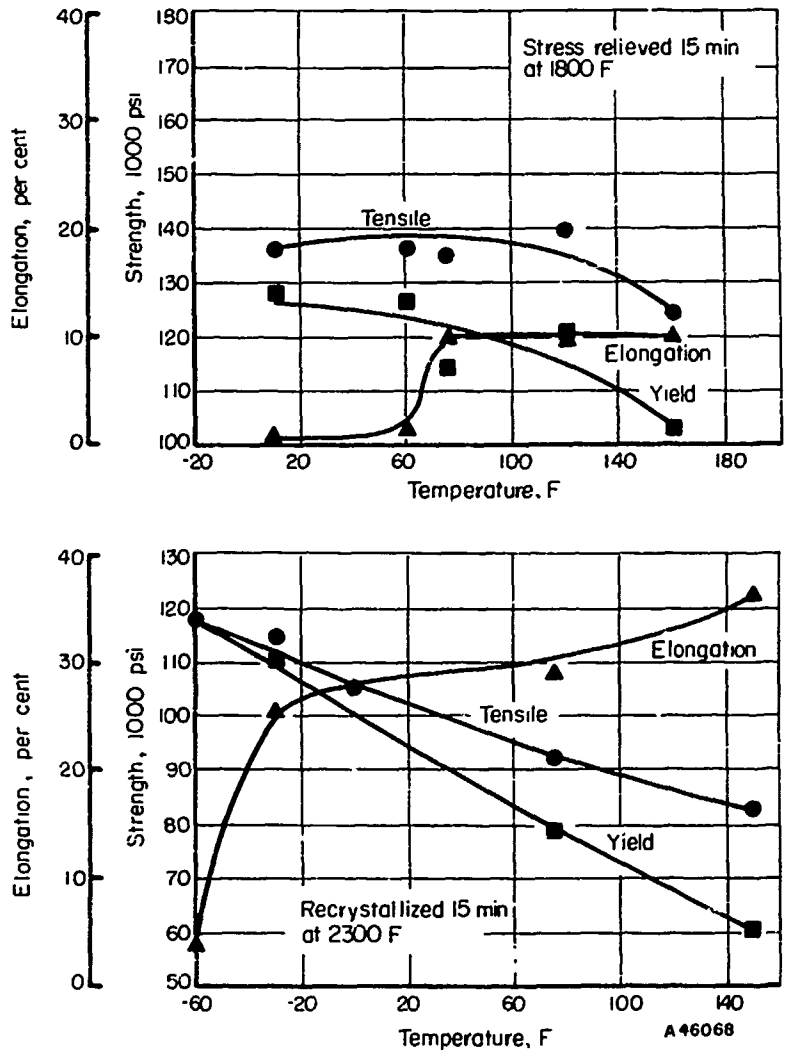
(a) Test rate 0.005 inch per inch per minute in the elastic range, then 0.05 inch per inch per minute to fracture.
(b) Sheet rolled in air with a relatively low finishing temperature.
(c) Sheet rolled in air with a relatively high finishing temperature.



Heat 4051-L, analyses 1.35% Cb and 0.028% C.

Sheet rolled in air with a relatively low finishing temperature.

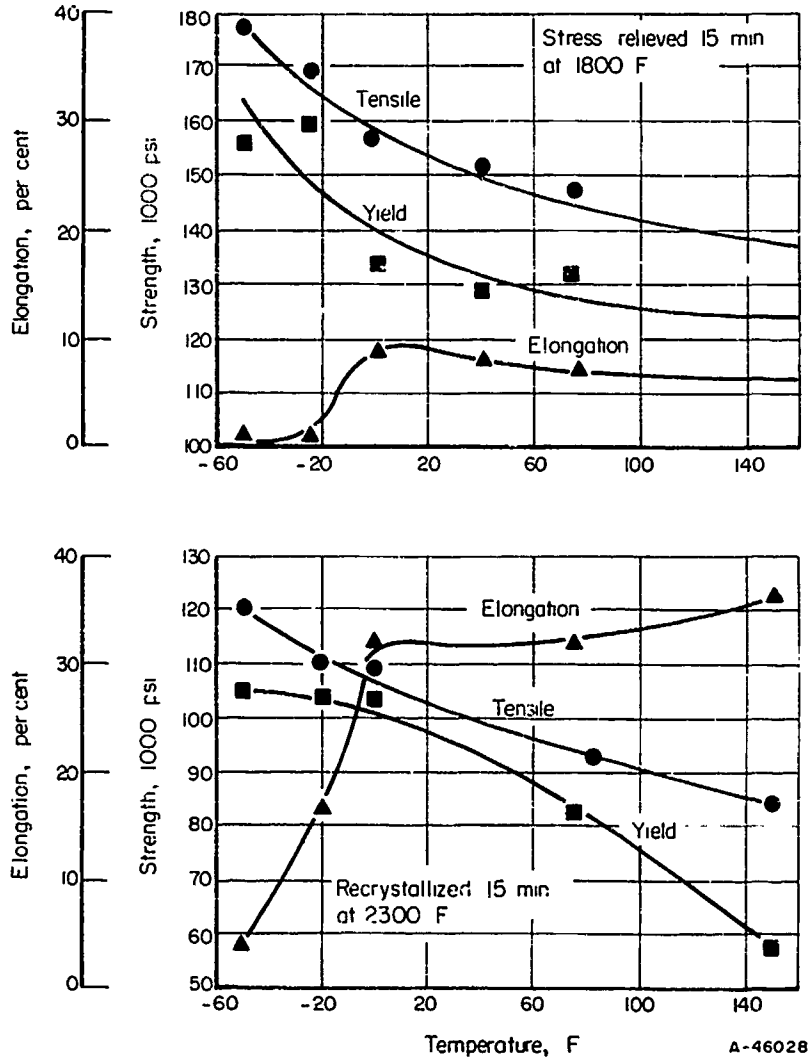
FIGURE A-70. LOW-TEMPERATURE TENSILE PROPERTIES OF LONGITUDINAL STRESS-RELIEVED AND RECRYSTALLIZED Mo-1.5Cb SHEET (0.050 INCH)[2]



Sheet rolled in air with a relatively high finishing temperature.

Heat 4051-H, analyses 1.35% Cb and 0.028% C.

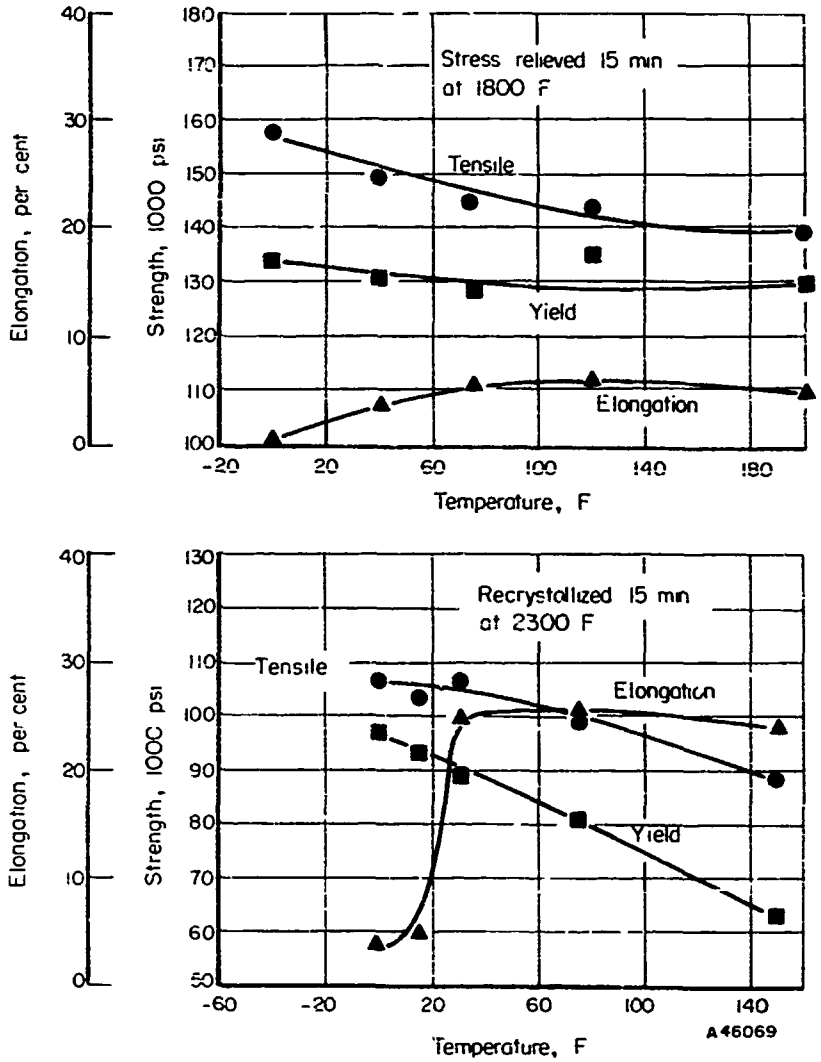
FIGURE A-70 (CONTINUED)



Sheet rolled in air with a relatively low finishing temperature.

Heat 4051-L, analyses 1.35% Cb and 0.028% C.

FIGURE A-71. LOW-TEMPERATURE TENSILE PROPERTIES OF TRANSVERSE STRESS-RELIEVED AND RECRYSTALLIZED Mo-1.5Cb SHEET (0.050 INCH)[2]



Sheet rolled in air with a relatively high finishing temperature.

Heat 4051-II, analyses 1.55% Cb and 0.023% C.

FIGURE A-71. (CONTINUED)

TABLE A-25. CREEP AND STRESS-RUPTURE BEHAVIOR OF Mo-1.5Cb BAR (3/16-INCH DIAMETER) AT 1800 AND 2400 F[1]

Composition (Balance Molybdenum), weight per cent	Condition	Stress, 1000 psi	Minimum Creep Rate, per cent hour	Rupture Time, hours	Elongation, per cent	Reduction in Area, per cent
		1800 F				
1.41Cb-0.047C	Stress relieved, 1 hour 2100 F	75.0	0.33	17.1	16.4	76.9
		70.0	0.08	68.3	18.1	76.1
1.41Cb-0.047C	Recrystallized, 1 hour 2550 F	39.0	0.92	17.8	62.3	87.3
		35.0	0.093	234.3	44.1	78.1
1.45Cb-0.25C	Stress relieved, 1 hour 2000 F	88.0	0.35	18.7	16.0	83.1
		80.0	0.20	32.8	19.0	73.8
1.45Cb-0.25C	Recrystallized, 1 hour 2700 F	43.0	0.15	146.0	47.7	70.5
		2400 F				
1.41Cb-0.047C	Stress relieved, 1 hour 2100 F	15.0	--	0.3[a]	15.6	21.5
		12.[illegible]	0.30	49.5	51.2	97.3
1.41Cb-0.047C	Recrystallized, 1 hour 2550 F	15.0	3.50	5.2	37.5	84.8
		11.0	1.20	0.8[a]	8.5	26.7
1.45Cb-0.25C	Stress relieved, 1 hour 2000 F	25.0	0.60	3.1	40.8	83.2
		18.0	0.18	11.6	37.6	84.0
1.45Cb-0.25C	Recrystallized, 1 hour 2700 F	16.0	1.80	17.0	51.2	90.1
		12.5	0.07	53.2	44.1	90.1

(a) Specimen overheated.

TABLE A-26. 100-HOUR RUPTURE STRENGTH FOR STRESS-RELIEVED AND RECRYSTALLIZED Mo-1.5Cb BAR (3/16-INCH DIAMETER) AT 1800 AND 2400 F[1]

Composition (Balance Molybdenum), weight per cent	Condition	100-Hour Rupture Stress, 1000 psi, to Produce Rupture at Indicated Temperature	
		1800 F	2400 F
1.41Cb-0.047C	Stress relieved	68.5	11.5
	Recrystallized	37.1	9.4
1.45Cb-0.25C	Stress relieved	80.0	12.3
	Recrystallized	43.5	11.8

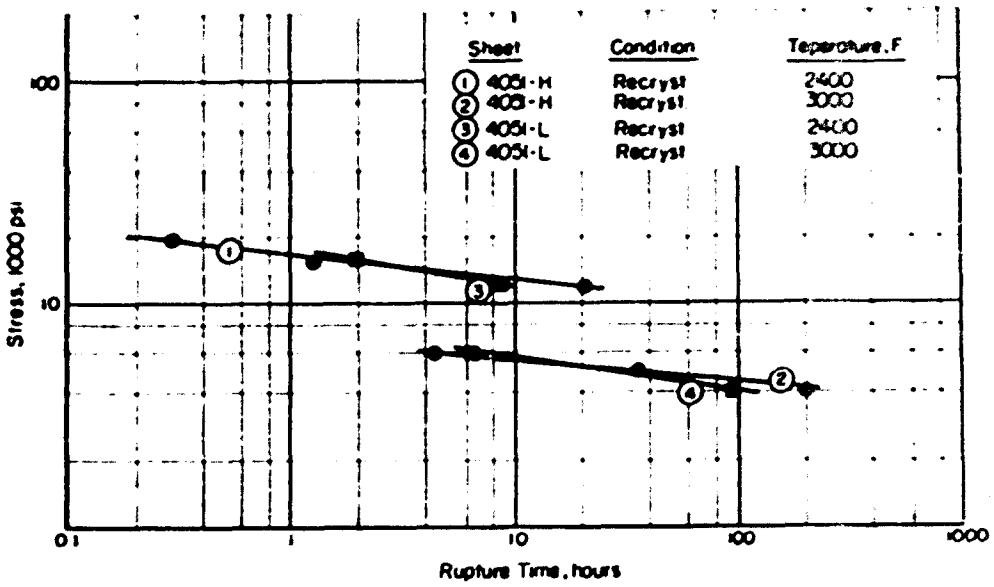


FIGURE A-72. STRESS-RUPTURE BEHAVIOR OF RECRYSTALLIZED Mo-1.5Cb SHEET AT 2400 AND 3000 F[2]

4051-L sheet rolled in air with a relatively low finishing temperature.

4051-H sheet rolled in air with a relatively high finishing temperature.

Analyses 1.35% Cb and 0.028% C.

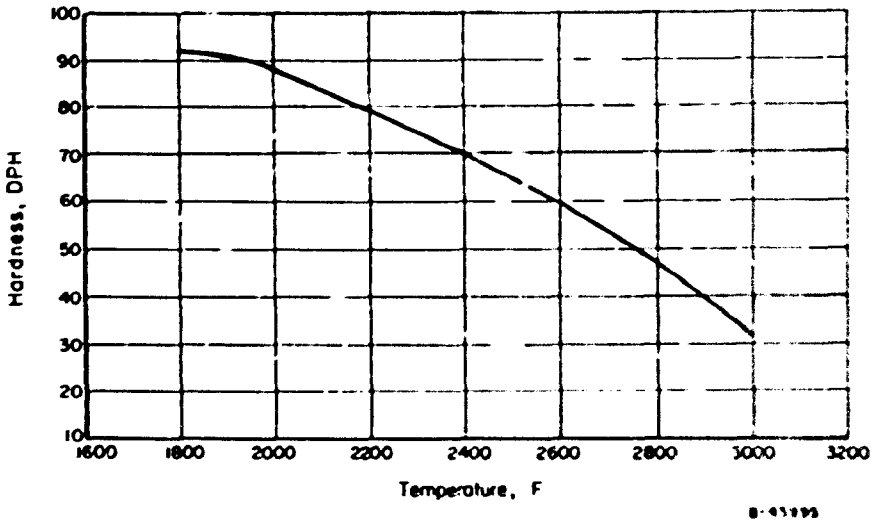


FIGURE A-73. EFFECT OF TEMPERATURE ON THE HOT HARDNESS OF ARC-CAST Mo-1.5Cb

Analyses 1.35% Cb and 0.028% C.

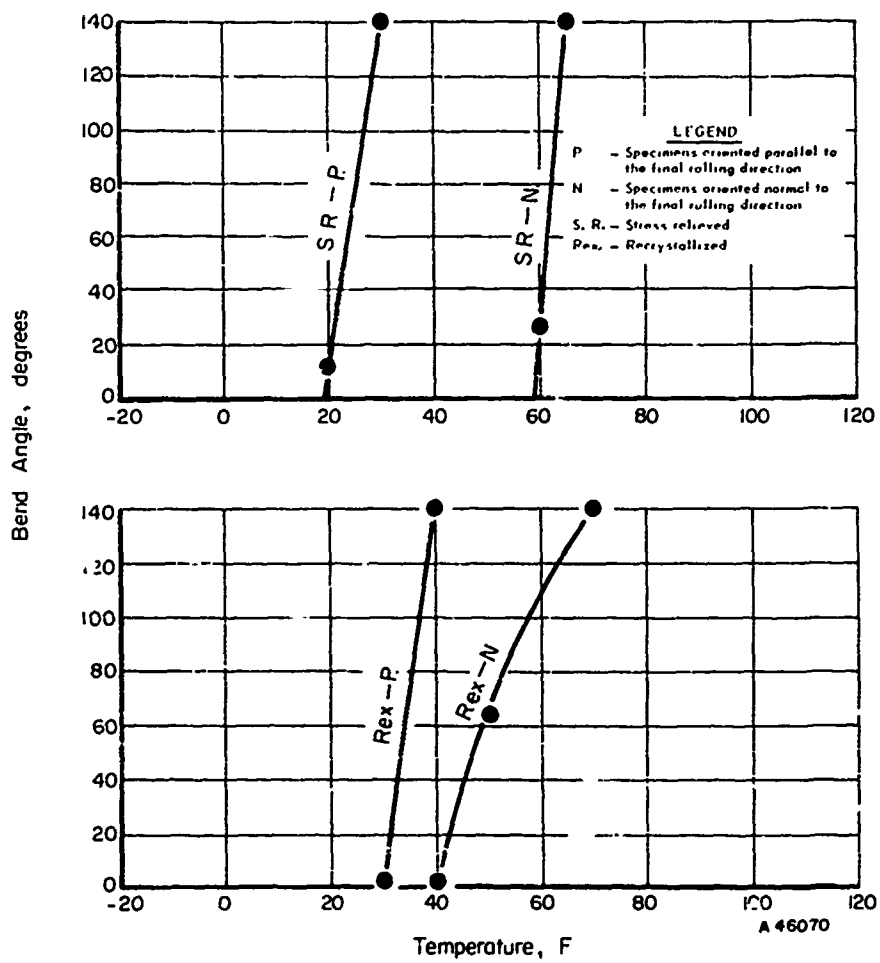


FIGURE A-74. BEND-DUCTILITY BEHAVIOR OF STRESS-RELIEVED AND RECRYSTALLIZED Mo-1.5Cb SHEET (0.051 INCH)[2]

Sheet rolled in air with a relatively low finishing temperature.

Heat 4051-L, analyses 1.35% Cb and 0.028% C.

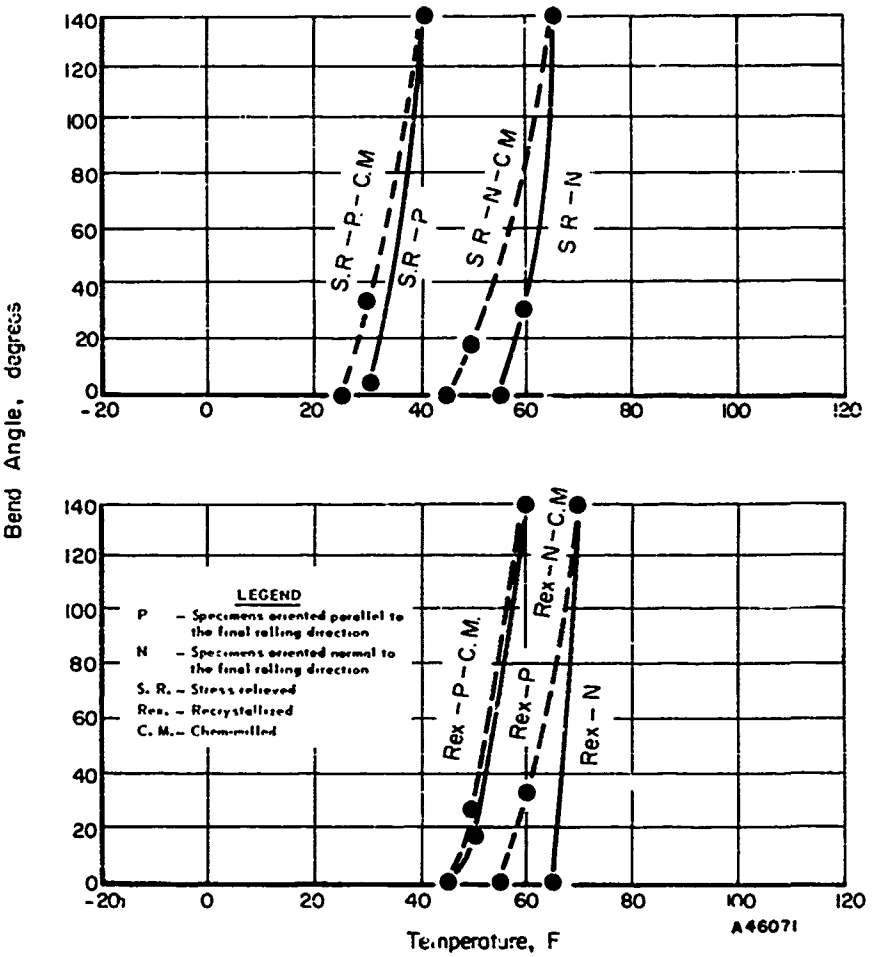


FIGURE A-75. EFFECT OF TEMPERATURE, THERMAL TREATMENT, AND SURFACE CONDITION ON THE BEND DUCTILITY OF Mo-1.5Cb SHEET (0.049 INCH)[2]

Sheet rolled in air with a relatively high finishing temperature.

Specimen chemically milled to 0.046 inch.

Heat 4051-H, analyses 1.35% Cb and 0.028% C.

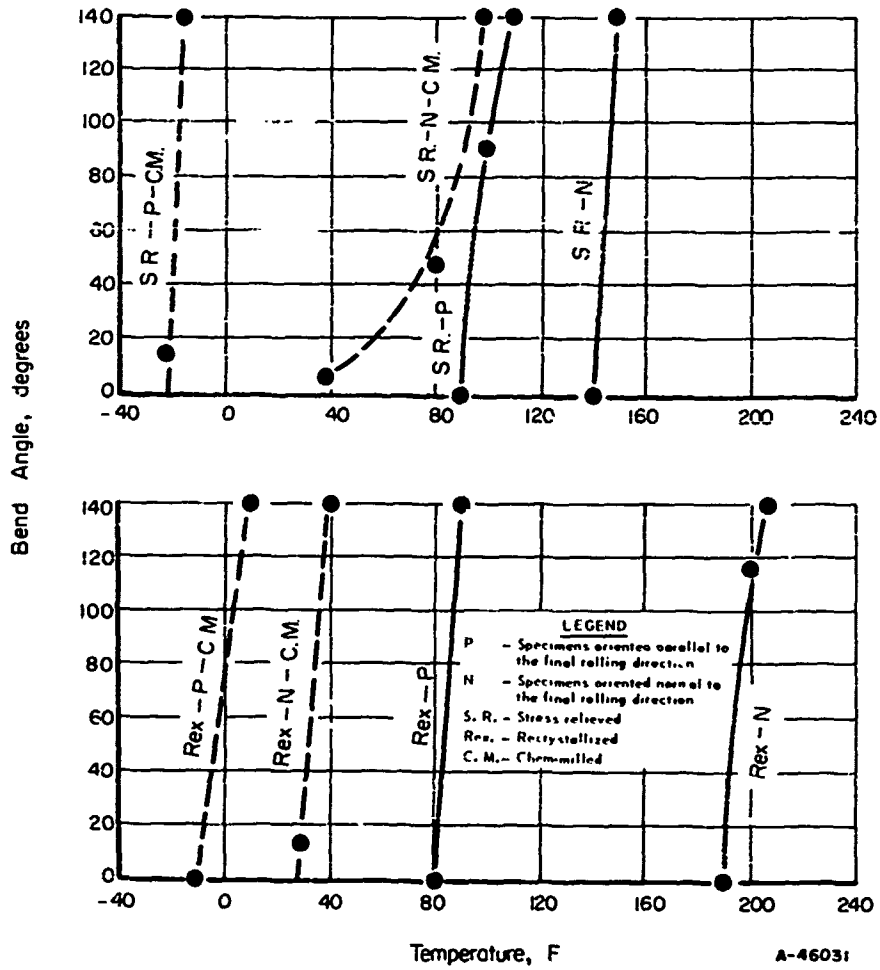


FIGURE A-76. EFFECT OF TEMPERATURE, THERMAL TREATMENT, AND SURFACE CONDITION ON THE BEND DUCTILITY OF Mo-1.5Cb SHEET (0.056 TO 0.059 INCH)[2]

Rolled in InFab facility.

Specimen chemically milled to 0.053 inch.

Heat 4051-I, analyses 1.35% Cb and 0.028% C.

4. Metallurgical Properties

a. Fabricability: arc-cast ingots can be extruded to sheet bar at 2800 to 3000 F using reduction ratios of up to 7:1, sheet bar can be rolled to intermediate gage thickness (1/8 inch) at 2400 F; final sheet rolling to 0.050 inch can be done at 1500 to 2000 F[2]

b. Transition temperature: -58 to 225 F depending upon fabrication history, thermal treatment, and surface condition[2]

c. Stress-relief temperature: 1 hour at 2000 to 2100 F for bar material[1]; 1/4 hour at 2000 F for sheet (0.050 inch) material[2]

d. Recrystallization temperature: 1 hour at 2550 to 2700 F for bar material[1]

Tables A-27 and A-28

TABLE A-27. EFFECT OF ANNEALING TEMPERATURE ON THE HARDNESS OF Mo-1.5Cb EXTRUDED SHEET BARS[a][2]

Extrusion Temperature, F	Extrusion Ratio	Hardness, DPH, After Annealing 1-Hour at Indicated Temperature, F					
		As Extruded	2600	2800	3000	3200	3300
2800	4.1:1	230	218	207	206	194[b]	--
3000	4.5:1	247	203	208	199	188[b]	--
3200	5.5:1	209	209	--	--	192	175[b]
3000	5.4:1	224	227	--	184	--	--
3000	7.1:1	231	215	213	198	199[b]	--

(a) Analysis 1.35% Cb and 0.028% C.
(b) 100 per cent recrystallized.

TABLE A-28. HARDNESS AND RECRYSTALLIZATION BEHAVIOR OF Mo-1.5Cb SHEET (0.059 INCH)[a][2]

1/4-Hour Annealing Temperature, F	Sheet Rolled in Air With a Relatively Low Finishing Temperature		Sheet Rolled in Air With a Relatively High Finishing Temperature		Sheet Rolled in In Fab Facility	
	Hardness, DPH	Recrystallization, per cent	Hardness, DPH	Recrystallization, per cent	Hardness, DPH	Recrystallization, per cent
As rolled	332	0	327	0	319	0
1800	319	0	310	0	--	--
2000	304	0	303	0	297	0
2050	--	--	--	--	291	5
2100	297	5	296	2	256	40
2200	252	60	253	40	194	100
2250	235	90	241	80	--	--
2300	181	100	193	100	--	--

(a) Analysis 1.35% Cb and 0.028% C.

References

(1) Semchyshen, M., McArdle, G. D., and Barr, R. Q., "Development of Molybdenum-Base Alloys". Climax Molybdenum Co., WADC TR 59-280 (October, 1959).

(2) McArdle, G. D., Barr, R. Q., and Semchyshen, M., "Investigation of Molybdenum- and Tungsten-Base Alloy Sheet Materials", Climax Molybdenum Co., Contract No. NOw 61-0581-d, Final Report (January 15, 1963).

Mo-0.05Zr

1. Identification of Material

   a. Chemical composition: Mo-0.05Z

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

2. Physical Properties

   a. Melting point: ~4730 F (essentially the same as that for unalloyed molybdenum)

   b. Density: 0.369 lb/in.^{3} (calculated)

3. Mechanical Properties

   a. Tensile Properties at Room Temperature

      Ultimate tensile strength: Table A-29

      Tensile yield strength: Table A-29

      Elongation: Table A-29

      Reduction in area: Table A-29

   b. Effect of Temperature on Tensile Properties

      Ultimate tensile strength: Table A-30
      Figures A-77 through A-79

      Tensile yield strength: Table A-30
      Figures A-77 through A-79

      Elongation: Table A-30
      Figures A-77 through A-79

      Reduction in area: Table A-30
      Figures A-77 through A-79

   c. Creep and Stress-Rupture Properties

      Tables A-31 and A-32

   d. Other Selected Mechanical Properties

      Bend ductility: Table A-33
      Figure A-80

TABLE A-29. ROOM-TEMPERATURE TENSILE PROPERTIES OF Mo-0.05Zr ROD AND SHEET

Composition (Balance Molybdenum), weight per cent	Condition	Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation, per cent	Reduction in Area, per cent	Reference
		Rod (5/8-Inch Diameter)				
0.054Zr-0.018C	As rolled	127.7	108.1	20	60.5	(1)
0.054Zr-0.018C	Stress relieved	126.4	111.0	26	58.9	(1)
0.054Zr-0.024C	Stress relieved	129.9	-	32	65.0	(2)
0.054Zr-0.02[illegible]C	Stress relieved	129.9	--	32	64.9	(2)
0.054Zr-0.018C	Recrystallized	75.6	59.3	23	18.9	(1)
		Sheet (1/16 inch)				
0.05Zr-0.022C	As rolled	145.6(L)	129.3(L)	5.0(L)	--	(3)
0.05Zr-0.022C	As rolled	156.4(T)	133.7(T)	3.5(T)	--	(3)
0.05Zr-0.022C	Stress relieved[a]	126.0(L)	115.8(L)	13.0(L)	--	(3)
0.05Zr-0.022C	Stress relieved[a]	131.0(T)	122.9(T)	9.0(T)	--	(3)
0.05Zr-0.022C	Recrystallized[b]	78.8(L)	63.5(L)	40.0(L)	--	(3)
0.05Zr-0.022C	Recrystallized[b]	80.2(T)	65.2(T)	36.0(T)	--	(3)
0.05Zr-0.053C	As rolled	122.2(L)	106.0(L)	9.5(L)	--	(3)
0.05Zr-0.053C	As rolled	129.1(T)	109.5(T)	6.5(T)	--	(3)
0.05Zr-0.053C	Stress relieved[a]	115.2(L)	99.1(L)	15.5(L)	--	(3)
0.05Zr-0.053C	Stress relieved[a]	120.1(T)	101.3(T)	11.5(T)	--	(3)
0.05Zr-0.053C	Recrystallized[c]	65.9(L)	56.0(L)	39.0(L)	--	(3)
0.05Zr-0.053C	Recrystallized[c]	78.9(T)	69.0(T)	44.0(T)	--	(3)

(a) Stress relieved 1 hour at 2000 F.
(b) Recrystallized 1 hour at 2550 F.
(c) Recrystallized 1 hour at 2500 F.

TABLE A-30. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF Mo-0.05Zr ROD AND SHEET

Composition (Balance Molybdenum), weight per cent	Temperature, F	Condition	Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation, per cent	Reduction in Area, per cent	Reference
		Rod (5/8-inch Diameter)					
0.054Zr-0.018C	600	As rolled	69.6	53.6	17	75	(1)
0.054Zr-0.018C	1600	Stress relieved	51.0	42.3	14	72	(1)
0.054Zr-0.018C	1600	Recrystallized	32.9	17.6	46	79	(1)
0.054Zr-0.024C	1800	Stress relieved	78.7	-	30	65	(4)
0.054Zr-0.024C	1800	Stress relieved	78.5	--	32	64.9	(4)
0.054Zr-0.024C	2000	Stress relieved	69.2	55.3	15	70.1	(4)
0.054Zr-0.024C	2100	Stress relieved	69.7	57.9	11	54.2	(4)
0.054Zr-0.018C	2400	Stress relieved	31.8	25.2	33	91.6	(5)
0.054Zr-0.024C	2400	Stress relieved	21.0	17.0	26	92.2	(4)
0.054Zr-0.024C	2400	Stress relieved	22.9	18.4	23	91.3	(4)
0.054Zr-0.018C	2400	Recrystallized	20.6	12.8	59	94.5	(5)
		Sheet (1/16 Inch)					
0.05Zr-0.022C	1800	As rolled	78.8 (L)	--	1.0 (L)	--	(3)
0.05Zr-0.022C	1800	As rolled	77.8 (T)	29.6 (T)	2.5 (T)	--	(3)
0.05Zr-0.022C	1800	Stress relieved[a]	79.8 (L)	--	2.0 (L)	--	(3)
0.05Zr-0.022C	1800	Stress relieved[a]	78.6 (T)	--	2.0 (T)	--	(3)
0.05Zr-0.022C	1800	Recrystallized[b]	31.9 (L)	14.2 (L)	25.0 (L)	--	(3)
0.05Zr-0.022C	1800	Recrystallized[b]	31.6 (T)	17.2 (T)	23.0 (T)	--	(3)
0.05Zr-0.053C	1800	As rolled	55.6 (L)	39.0 (L)	5.0 (L)	--	(3)
0.05Zr-0.053C	1800	As rolled	61.3 (T)	--	4.0 (T)	--	(3)
0.05Zr-0.053C	1800	Stress relieved[a]	60.6 (L)	--	3.0 (L)	--	(3)
0.05Zr-0.053C	1800	Stress relieved[a]	62.9 (T)	--	4.0 (T)	--	(3)
0.05Zr-0.053C	1800	Recrystallized[c]	28.5 (L)	13.8 (L)	8.0 (L)	--	(3)
0.05Zr-0.053C	1800	Recrystallized[c]	27.1 (T)	16.3 (T)	10.0 (T)	--	(3)
0.05Zr-0.022C	2400	Stress relieved[a]	21.3 (L)	--	14.0 (L)	--	(3)
0.05Zr-0.022C	2400	Stress relieved[a]	19.7 (T)	10.3 (T)	16.0 (T)	--	(3)
0.05Zr-0.022C	2400	Recrystallized[b]	19.2 (L)	10.4 (L)	29.0 (L)	--	(3)
0.05Zr-0.022C	2400	Recrystallized[b]	18.2 (T)	6.5 (T)	10.0 (T)	--	(3)
0.05Zr-0.053C	2400	Stress relieved[a]	17.1 (L)	9.3 (L)	25.0 (L)	--	(3)
0.05Zr-0.053C	2400	Stress relieved[a]	17.1 (T)	7.3 (T)	26.0 (T)	--	(3)
0.05Zr-0.053C	2400	Recrystallized[c]	16.9 (L)	6.0 (L)	27.0 (L)	--	(3)
0.05Zr-0.053C	2400	Recrystallized[c]	16.4 (T)	7.9 (T)	29.0 (T)	--	(3)

(a) Stress relieved 1 hour at 2000 F.
(b) Recrystallized 1 hour at 2500 F.
(c) Recrystallized 1 hour at 2600 F.

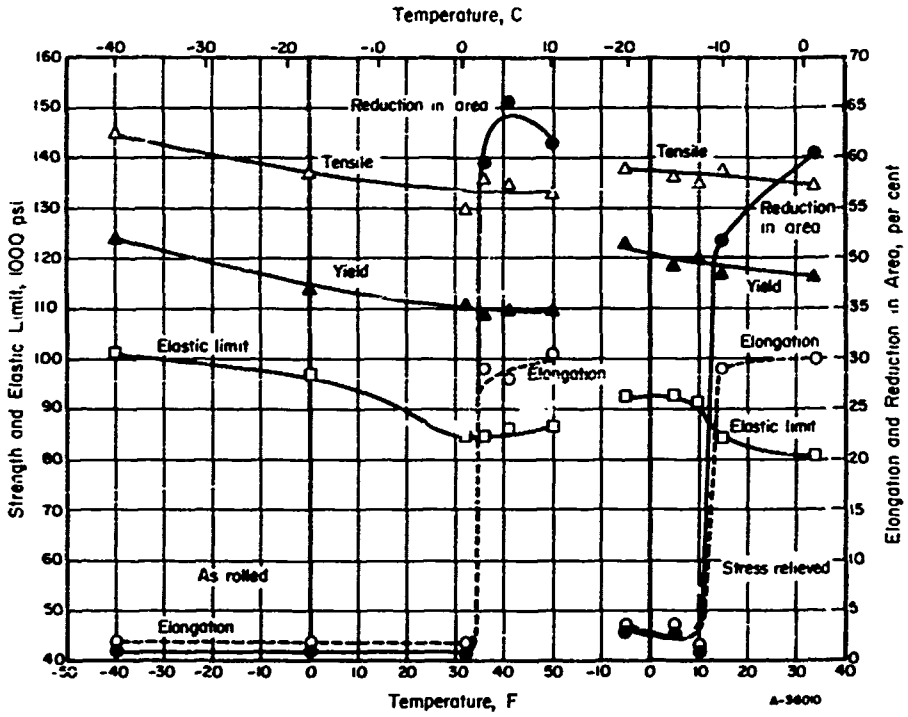


FIGURE A-77. LOW-TEMPERATURE TENSILE PROPERTIES OF Mo-0.05Zr BAR (5/8-INCH DIAMETER) IN THE AS-ROLLED AND STRESS-RELIEVED CONDITIONS[1]

Stress relieved 1 hour at 1800 F.

Analyses 0.054% Zr and 0.018% C.

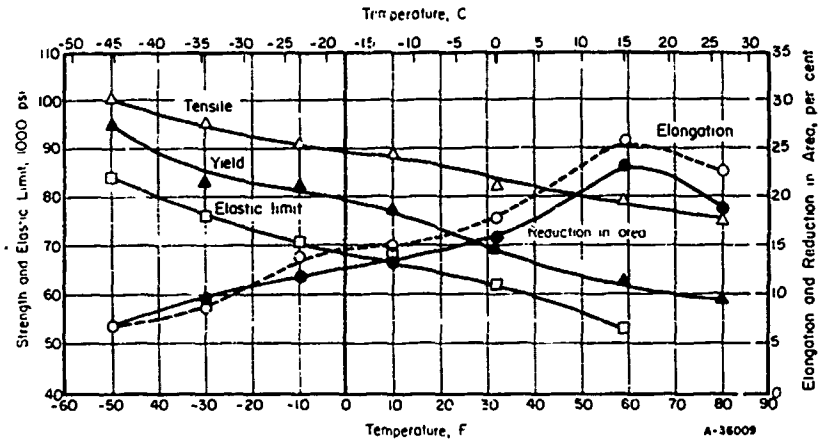


FIGURE A-78. LOW-TEMPERATURE TENSILE PROPERTIES OF RECRYSTALLIZED Mo-0.05Zr BAR (5/8-INCH DIAMETER)[1]

Recrystallized 1 hour at 2450 F.

Analyses 0.054% Zr and 0.018% C.

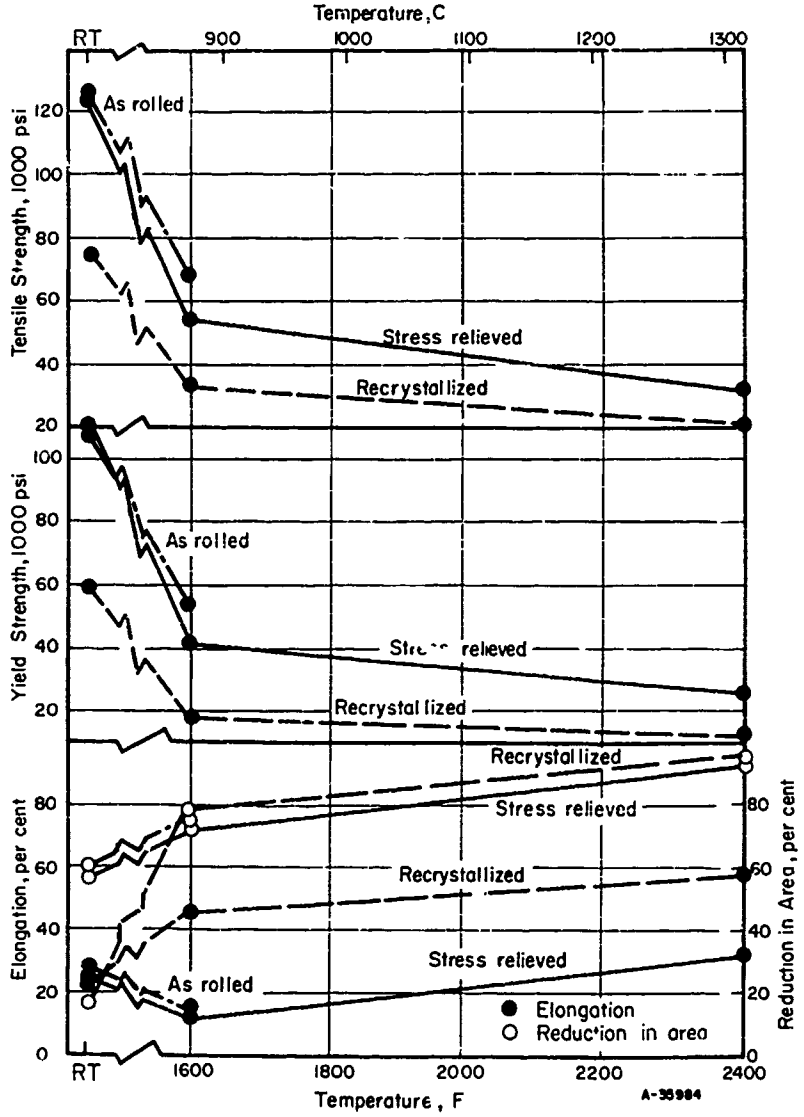


FIGURE A-79. EFFECT OF TEMPERATURE AND CONDITION ON THE TENSILE PROPERTIES OF Mo-0.05Zr[5]

TABLE A-31. STRESS-RUPTURE DATA FOR STRESS RELIEVED AND RECRYSTALLIZED Mo 0.05Zr SHEET (1/16 INCH) AT 1600 F[3]

Carbon Content, weight per cent	Condition	Stress, 1000 psi, to Produce Rupture		
		1 Hour	10 Hours	100 Hours
0.022	Stress relieved 1 hour at 2000 F	74.5	64.0	56.0
	Recrystallized 1 hour at 2550 F	30.0	26.5	23.5
0.053	Stress relieved 1 hour at 2000 F	58.0	51.0	45.0
	Recrystallized 1 hour at 2500 F	31.5	26.0	21.5

TABLE A-32. CREEP AND STRESS-RUPTURE PROPERTIES OF AS-ROLLED, STRESS-RELIEVED, AND RECRYSTALLIZED Mo-0.05Zr AT 1600 TO 2400 F[a]

Condition	Temperature, F	Stress, 1000 psi	Creep Rate, per cent/hour	Rupture Time, hours	Elongation, per cent	Reduction in Area, per cent	Reference
Stress relieved	1600	80.0	0.[illegible]	16.8	1[illegible].8	73.0	(1)
		72.0	0.028	176.1	15.5	73.5	(1)
		65.0	0.0010	194.1[b]	--	--	(1)
	1800	70.0	0.24	20.5	14.9	75.4	(1)
		62.0	0.05	171.7	18.5	70.6	(1)
		55.0	0.010	259.1[b]	--	--	(1)
	2000	45.0	0.1	62.8	12.3	81.9	(1)
		30.0	0.0037	405.2	13.6	2.9	(6)
Recrystallized	1600	40.0	--	0.4	40.2	93.6	(1)
		33.0	0.55	31.0	26.8	95.0	(1)
	1800	35.0	--	0.2	41.5	94.8	(1)
		25.0	0.063	150.7	28.1	87.9	(1)
	2000	30.0	--	0.2	50.8	95.0	(1)
		21.5	0.0[illegible]	84.3	2[illegible]	81.0	(1)
As rolled	2400	15.0	0.90	11.3	19.5	89.6	(6)
		10.0	0.56	147.3	14.1	10.5	(6)

(a) Analyses 0.054% Zr and 0.018% C.
(b) Test discontinued.

TABLE A-33. BEND-TEST DATA FOR Mo-0.05Zr SHEET (1/16 INCH)[3]

Carbon Content, weight per cent	Condition	Specimen Orientation[a], degrees	Temperature, F, for Indicated Bend Angle		Bend Angle at 75 F, degrees
			10 Degrees	90 Degrees	
0.022	As rolled	0	>-140	18	140
	Stress relieved	0	23	52	140
	Recrystallized	0	68	72	140
	As rolled	90	-75	190	46
	Stress relieved	90	-59	-54	140
	Recrystallized	90	8	22	140
0.053	As rolled	0	-48	48	140
	Stress relieved	0	60	115	31
	Recrystallized	0	130	132	0
	As rolled	90	-28	330	49
	Stress relieved	90	43	85	65
	Recrystallized	90	120	142	0

(a) Orientation of long dimension with rolling direction.

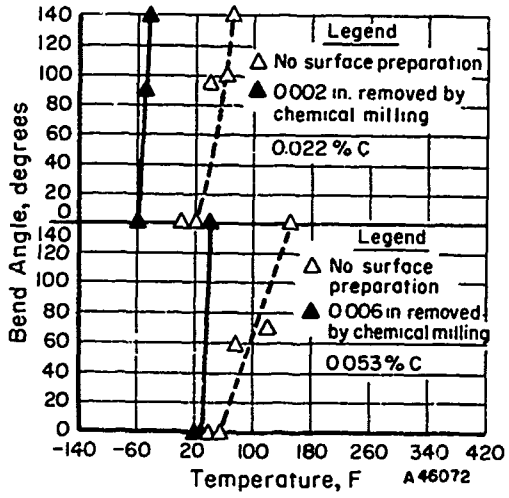


FIGURE A-80. EFFECT OF TEMPERATURE AND AMOUNT OF SURFACE REMOVED BY CHEMICAL MILLING ON THE BEND PROPERTIES OF STRESS-RELIEVED Mo-0.05Zr SHEET (1/16 INCH)[3]

Stress relieved 15 minutes at 2100 F.
Specimens cut parallel to rolling direction.

4. Metallurgical Properties

a. Fabricability: successful conversion to sheet product has been demonstrated by the following schedule (1) arc-cast ingot machined into an extrusion blank; (2) extruded; (3) extruded billet conditioned and recrystallized; (4) forged or rolled to a 1 to 2-inch-thick sheet bar; (5) sheet bar conditioned and recrystallized, (6) rolled to 1/4 to 3/8-inch-thick plate; (7) recrystallized; and (8) rolled to 1/16-inch sheet.[3]

b. Transition temperature: -60 to 50 F for sheet (1/16 inch) material, depending upon thermal history, carbon content, and sheet-surface condition[3]

c. Weldability: should behave similiar to unalloyed molybdenum; zirconium would tend to improve welding characteristics[7]

d. Stress-relief temperature: 1/4 to 1 hour at 2000 to 2100 F for sheet (1/16 inch) material[3]

e. Recrystallization temperature: 1/4 to 1 hour at 2500 to 2600 F for sheet (1/16 inch) material[3]

Figures A-81 and A-82

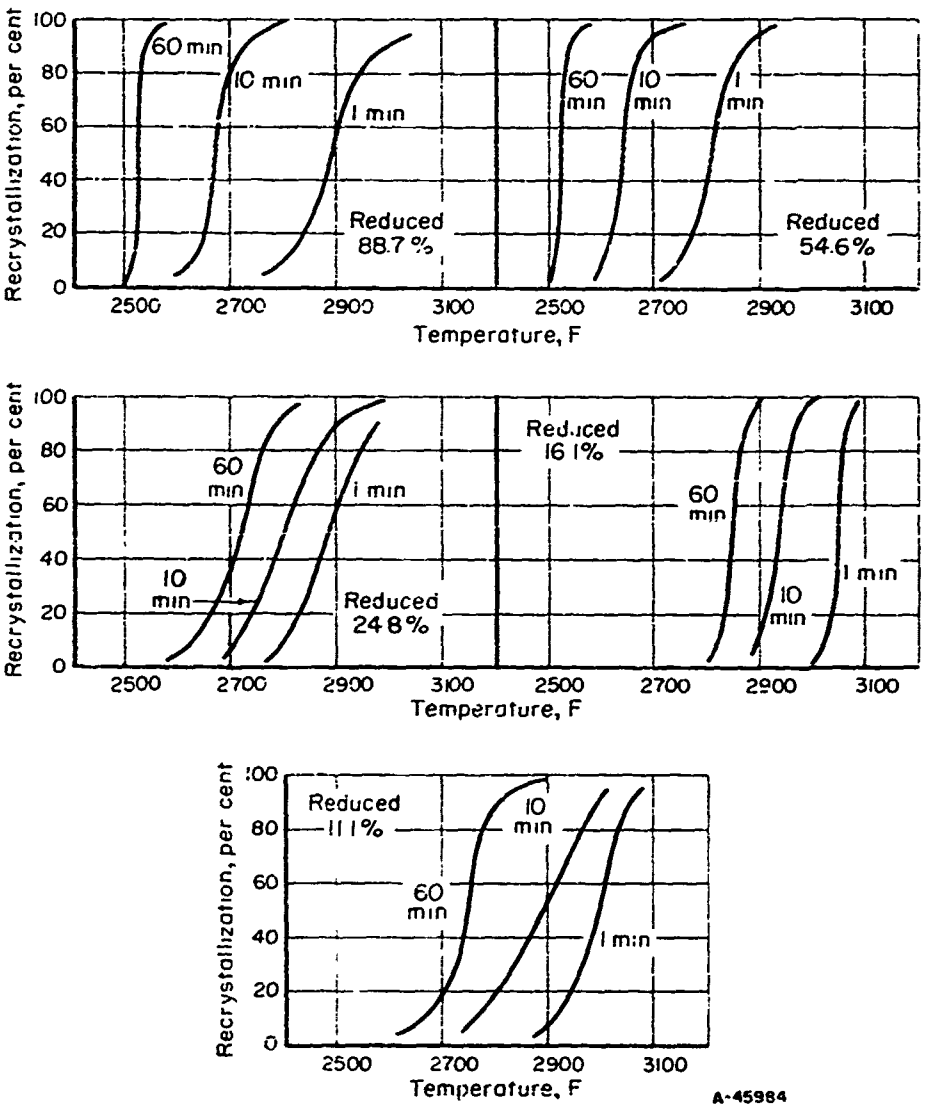
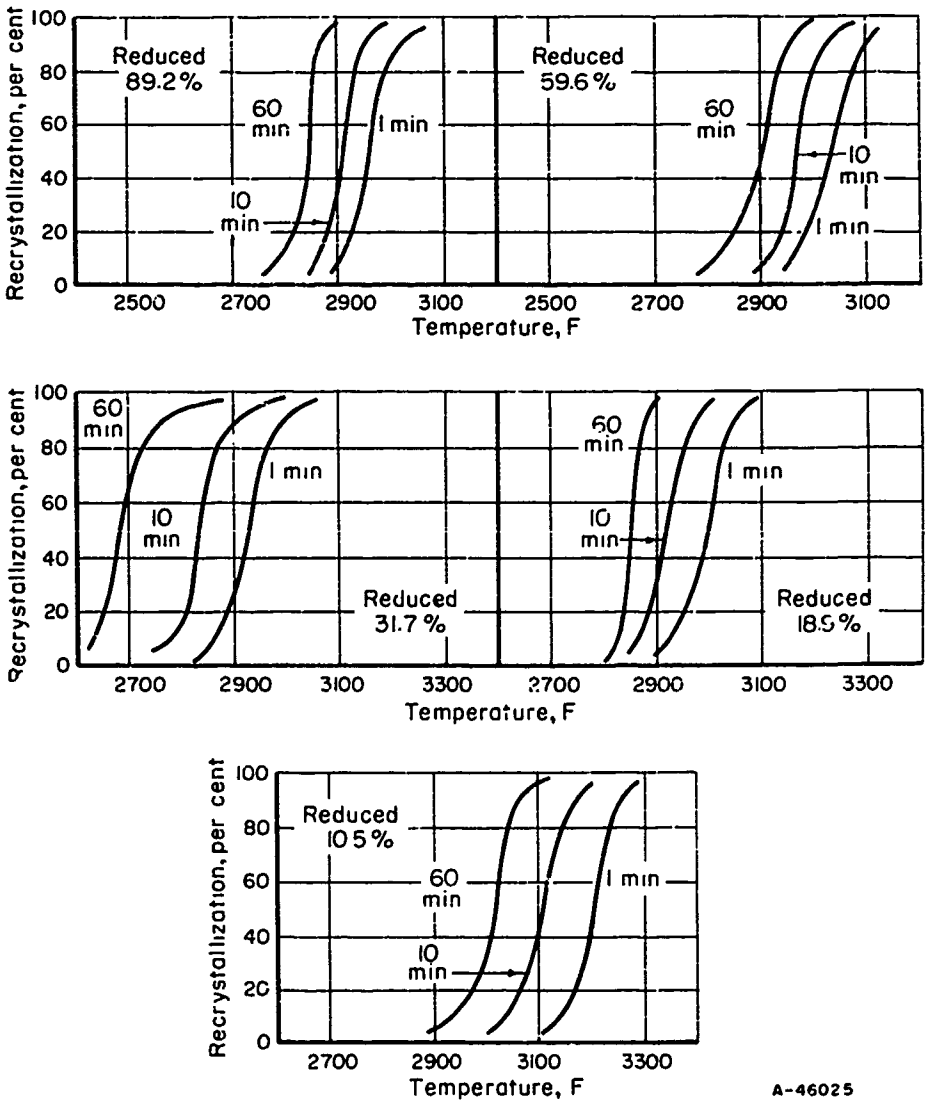


FIGURE A-81. RECRYSTALLIZATION BEHAVIOR AS A FUNCTION OF TIME AND TEMPERATURE FOR Mo-0.05Zr BARS ROLLED TO INDICATED REDUCTIONS[8]

Analysis 0.059% Zr and 0.010% C.



b. Rolled at 3000 F

FIGURE A-81. (CONTINUED)

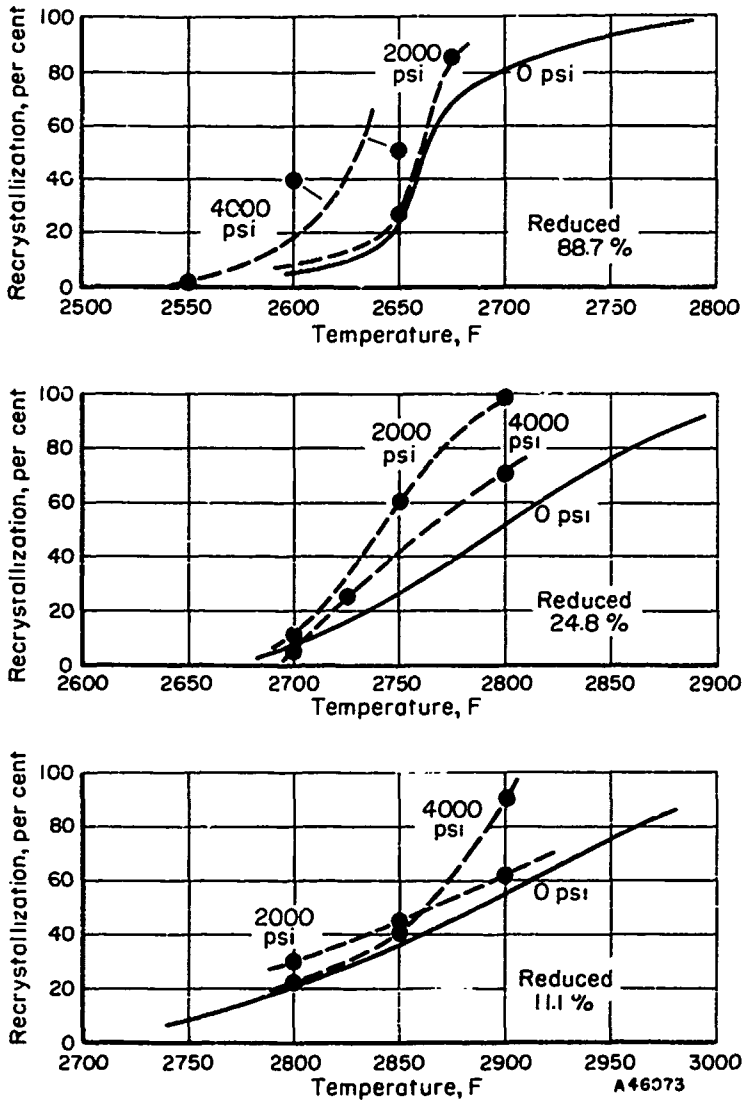


FIGURE A-82. RECRYSTALLIZATION BEHAVIOR AS A FUNCTION OF TEMPERATURE AND EXTERNALLY APPLIED STRESS FOR Mo-0.05Zr BARS[8]

Annealed for 10-minute periods.
Subjected to indicated reduction at 2200 F.
Analyses 0.059% Zr and 0.010% C.

References

(1) Semchyshen, M., and Barr, R. Q., "Arc Cast Molybdenum-Base Alloys", Climax Molybdenum Co., Contract No. N9onr-82100 (1955).

(2) Bruckart, W. L., Whalen, S. J., Jaffee, R. I., and Gonser, B. W., "Molybdenum Alloys and Protection by Cladding", Project Rand Report from Battelle Memorial Institute to United States Air Force (April 25, 1950).

(3) Semchyshen, M., and Barr, R. Q., "Mechanical Properties of Molybdenum and Molybdenum-Base Alloy Sheet", ASTM STP No. 272 (1959).

(4) Barr, R. Q., and Semchyshen, M., "Stress-Strain Curves for Wrought Molybdenum and Three Molybdenum-Base Alloys", Climax Molybdenum Co. (December, 1959).

(5) Semchyshen, M., McArdle, G. D., and Barr, R. Q., "Development of Molybdenum-Base Alloys", Climax Molybdenum Co., WADC TR 59-280 (October, 1959).

(6) Semchyshen, M., McArdle, G. D., and Barr, R. Q., "Development of High Strengths and High Recrystallization Temperatures in Molybdenum-Base Alloys", Climax Molybdenum Co., WADC TR 58-551 (February, 1959).

(7) Private communication from F. Nair, Climax Molybdenum Co. (1963).

(8) Semchyshen, M., and Barr, R. Q., "Extrusion and Mechanical Properties of Some Molybdenum- and Tungsten-Base Alloys", Climax Molybdenum Co., ASD TR 61-193 (May, 1961).

Mo-0.5Zr

1. Identification of Material

   a. Chemical composition: Mo-0.5Zr

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

2. Physical Properties

   a. Melting point: ~ 4730 F (essentially the same as that for unalloyed molybdenum)

   b. Density: 0.368 lb/in.^{3} (calculated)

3. Mechanical Properties

   a. Tensile Properties at Room Temperature

      Ultimate tensile strength: Table A-34

      Tensile yield strength: Table A-34

      Elongation: Table A-34

      Reduction in area: Table A-34

   b. Effect of Temperature on Tensile Properties

      Ultimate tensile strength: Tables A-35 through A-37
      Figures A-83 and A-84

      Tensile yield strength: Tables A-35 through A-37
      Figures A-83 and A-84

      Elongation: Tables A-35 through A-37
      Figures A-83 and A-84

      Reduction in area: Table A-36
      Figures A-83 and A-84

   c. Notched Tensile Properties

      Table A-38

   d. Creep and Stress-Rupture Properties

      Tables A-39 and A-40

e. Other Selected Mechanical Properties

Bend ductility: Table A-41

Shear strength: for sheet material[3]

Room Temperature		2500 F	
Stress, 1000 psi	Per Cent of TS	Stress, 1000 psi	Per Cent of TS
80.5	74.5	23.4	60.5
74.4	69.0	25.0	64.6

TABLE A-34. ROOM-TEMPERATURE TENSILE PROPERTIES OF Mo-0.5Zr ROD AND SHEET

Composition (Balance Molybdenum), weight per cent	Condition	Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation, per cent	Reduction in Area, per cent
	Rod (1/2-Inch Diameter)[1]				
0.19Zr-0.22C	As rolled	125.3	95.4	21	36
0.49Zr-0.022C	Stress relieved	118.7	80.8	33	55.6
0.52Zr-0.30C	Stress relieved	120.8	102.3	21	38.6
0.49Zr-0.022C	Recrystallized	85.0	63.4	49	50.1
	Sheet (0.045 Inch), Stress relieved 1 Hour at 2200 F[2]				
0.49Zr-0.014C	SR 60%, stress relieved	104 (L)	84 (L)	8.6 (L)	--
0.49Zr-0.014C	SR 60%, stress relieved	110.8 (T)	94 (T)	11 (T)	--
0.49Zr-0.014C	CR 60%, stress relieved	98.2 (L)	77.9 (L)	8.8 (L)	--
0.49Zr-0.014C	CR 60%, stress relieved	104.8 (T)	83.5 (T)	16.5 (T)	--
0.49Zr-0.014C	SR 75%, stress relieved	113 (L)	91.1 (L)	18.3 (L)	--
0.49Zr-0.014C	SR 75%, stress relieved	116 (T)	99.6 (T)	8.2 (T)	--
0.49Zr-0.014C	CR 75%, stress relieved	109 (L)	89 (L)	12.3 (L)	--
0.49Zr-0.014C	CR 75%, stress relieved	110 (T)	94.7 (T)	11.3 (T)	--
0.49Zr-0.014C	SR 90%, stress relieved	126 (L)	94 (L)	14.3 (L)	--
0.49Zr-0.014C	SR 90%, stress relieved	121.5 (T)	105.1 (T)	8.6 (T)	--
0.49Zr-0.014C	SR 90%, stress relieved	105.1(45 deg)	88.8(45 deg)	24.3(45 deg)	--
0.49Zr-0.014C	CR 90%, stress relieved	120.1 (L)	96 (L)	14.3 (L)	--
0.49Zr-0.014C	CR 90%, stress relieved	116.2 (T)	103.7 (T)	7.5 (T)	--

TABLE A-35. LOW-TEMPERATURE TENSILE PROPERTIES OF ANNEALED Mo-0.5Zr SHEET (0.040 INCH)[a][3]

Temperature, F	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation in 3/4 Inch, per cent
RT	108.3	83.6	15.8
	108.3	84.2	16.4
32	116.2	91.3	13.4
	114.4	91.1	15.1
0	115.8	98.4	6.0
	116.0	100.0	5.5
-40	113.0	103.2	3.5
	107.0	105.1	1.4

(a) Annealed 1 hour at 2200 F. Nominal carbon content 0.04 per cent.

TABLE A-36. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF Mo-0.5Zr ROD AND SHEET

Composition (Balance Molybdenum), weight per cent	Temperature, F	Condition	Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation, per cent	Reduction in Area, per cent	Reference
		Rod (1/2-Inch Diameter)					
0.19Zr-0.22C	-60	Stress relieved	129.9	110.0	3	3.2	(4)
0.19Zr-0.22C	-10	Recrystallized	73.7	55.2	4	3.0	(4)
0.19Zr-0.22C	0	Stress relieved	123.7	92.8	29	44	(4)
0.19Zr-0.22C	0	Recrystallized	78.0	49.3	5	4	(4)
0.49Zr-0.022C	1800	Stress relieved	72.7	62.8	10	34.3	(1)
0.52Zr-0.30C	1800	Stress relieved	77.5	--	18	38.2	(1)
0.49Zr-0.022C	1800	Recrystallized	47.0	--	40	88	(1)
0.49Zr-0.022C	2000	As rolled	80.0	68.3	13	82	(4)
0.49Zr-0.022C	2400	Stress relieved	26.6	24.[illegible]	27	24.6	(4)
0.52Zr-0.30C	2400	Stress relieved	46.3	32.5	19	60	(4)
0.49Zr-0.022C	2400	Recrystallized	23.0	10.9	81	93.2	(4)
		Sheet (0.045 Inch), Stress Relieved 1 Hour at 2200 F					
0.49Zr-0.014C	2000	SR 60%	57.2 (L)	54.1 (L)	2.5 (L)	--	(2)
0.49Zr-0.014C	2000	SR 60%	57.1 (T)	55.6 (T)	2.4 (T)	--	(2)
0.49Zr-0.014C	2000	CR 60%	55.8 (L)	49.0 (L)	3.6 (L)	--	(2)
0.49Zr-0.014C	2000	CR 60%	61.8 (T)	59.8 (T)	5.7 (T)	--	(2)
0.49Zr-0.014C	2000	SR 75%	63.3 (L)	56.5 (L)	3.7 (L)	--	(2)
0.49Zr-0.014C	2000	SR 75%	73.5 (T)	54.2 (T)	1.5 (T)	--	(2)
0.49Zr-0.014C	2000	CR 75%	64.5 (L)	55.2 (L)	4.7 (L)	--	(2)
0.49Zr-0.014C	2000	CR 75%	69.4 (T)	55.2 (T)	7.5 (T)	--	(2)
0.49Zr-0.014C	2000	SR 90%	68.5 (L)	64.5 (L)	7.1 (L)	--	(2)
0.49Zr-0.014C	2000	SR 90%	65.4 (T)	62.6 (T)	7.1 (T)	--	(2)
0.49Zr-0.014C	2000	SR 90%	54.0(45 deg)	53.6(45 deg)	7.1(45 deg)	--	(2)
0.49Zr-0.014C	2000	CR 90%	71.5 (L)	66.3 (L)	[illegible].9 (L)	--	(2)
0.49Zr-0.014C	2000	CR 90%	68.8 (T)	63.6 (T)	5.0 (T)	--	(2)
0.49Zr-0.014C	2200	SR 60%	40.5 (L)	36.8 (L)	3.1 (L)	--	(2)
0.49Zr-0.014C	2200	SR 60%	49.9 (T)	47.1 (T)	3.8 (T)	--	(2)
0.49Zr-0.014C	2200	CR 60%	45.5 (L)	35.1 (L)	7.2 (L)	--	(2)
0.49Zr-0.014C	2200	CR 60%	49.1 (T)	41.1 (T)	4.3 (T)	--	(2)
0.49Zr-0.014C	2200	SR 75%	47.0 (L)	40.6 (L)	6.3 (L)	--	(2)
0.49Zr-0.014C	2200	SR 75%	54.7 (T)	51.4 (T)	4.5 (T)	--	(2)
0.49Zr-0.014C	2200	CR 75%	50.0 (L)	42.1 (L)	3.7 (L)	--	(2)
0.49Zr-0.014C	2200	CR 75%	54.9 (T)	45.5 (T)	6.2 (T)	--	(2)
0.49Zr-0.014C	2200	SR 90%	44.5 (L)	38.1 (L)	5.9 (L)	--	(2)
0.49Zr-0.014C	2200	SR 90%	45.7 (T)	36.1 (T)	5.4 (T)	--	(2)
0.49Zr-0.014C	2200	SR 90%	42.1(45 deg)	35.3(45 deg)	7.1(45 deg)	--	(2)
0.49Zr-0.014C	2200	CR 90%	47.9 (L)	41.8 (L)	7.1 (L)	--	(2)
0.49Zr-0.014C	2200	CR 90%	44.8 (T)	49.3 (T)	5.0 (T)	--	(2)

TABLE [illegible]. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF STRESS-RELIEVED Mo-0.5Zr SHEET (0.040 INCH)[a][3]

Temperature, F	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation in 3/4 Inch, per cent
RT	105.4	86.1	16.3
	108.6	88.9	18.8
	110.2	86.7	18.8
1000	74.2	68.8	7.5
	74.9	69.8	6.2
	74.6	63.8	--
2200	44.6	40.1	9.5
	46.8	40.7	10.6
	46.8	42.1	10.0
2500	40.3	36.8	11.3
	37.0	31.2	16.2

(a) Stress relieved 1 hour at 2200 F. Test rate 0.005 inch per inch per minute to yield, then 0.03 inch per inch per minute to fracture. Nominal carbon content 0.04 per cent.

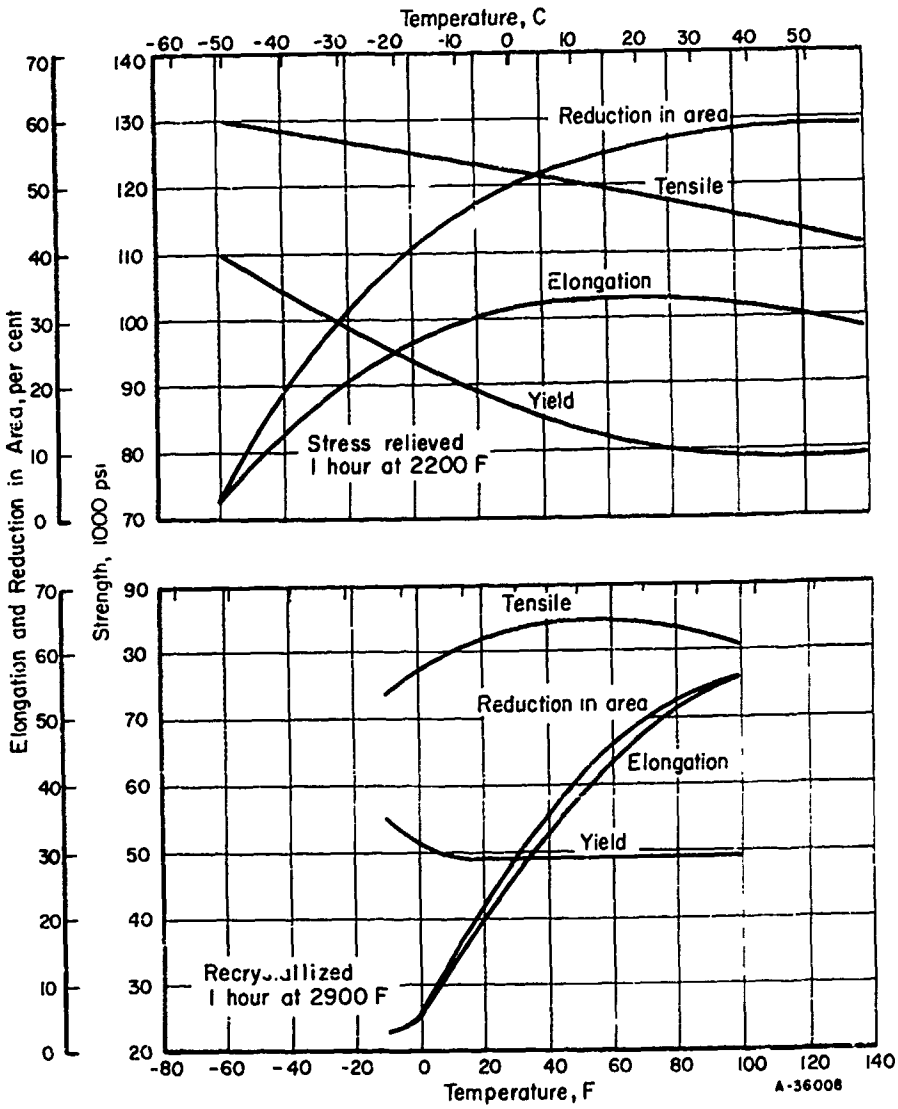


FIGURE A-83. LOW-TEMPERATURE TENSILE PROPERTIES OF STRESS-RELIEVED AND RECRYSTALLIZED Mo-0.5Zr BAR (1/2-INCH DIAMETER)[4]

Analyses 0.47% Zr and 0.022% C.

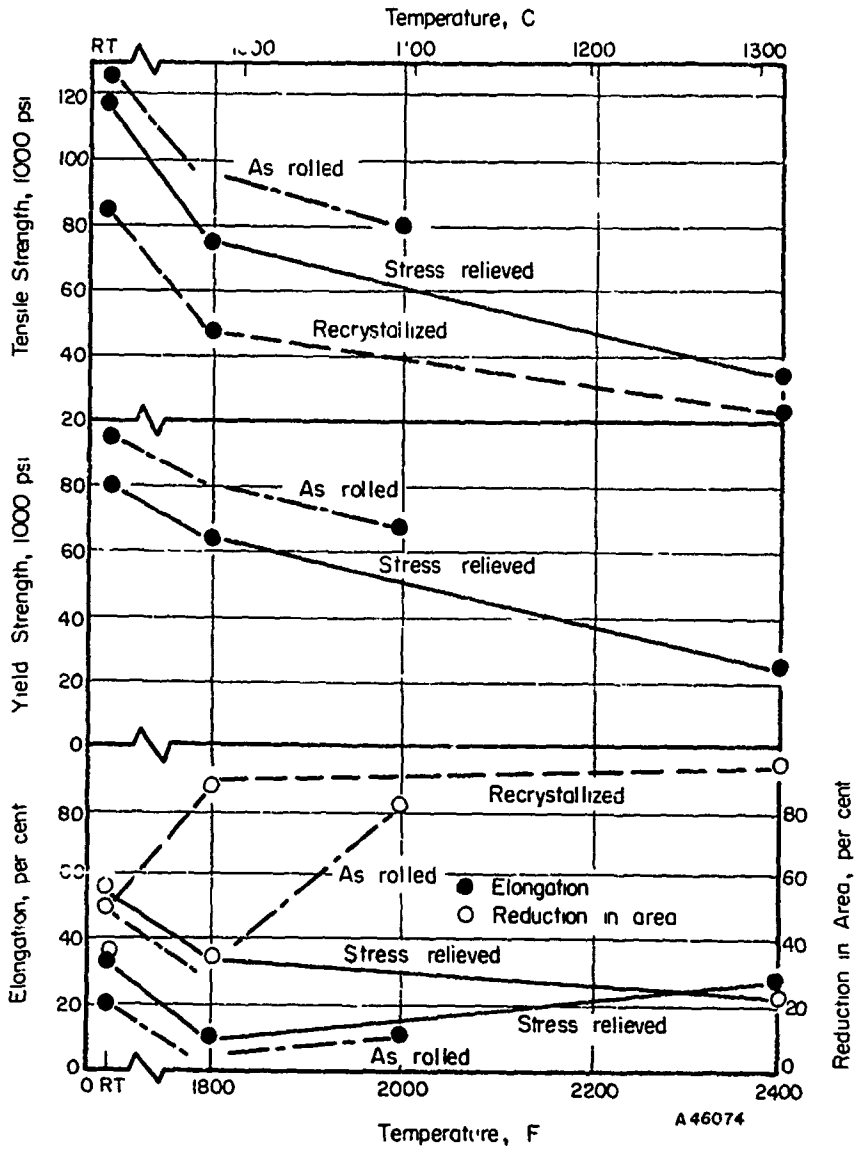


FIGURE A-64. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF Mo-0.5Zr(1)

TABLE A-38. ROOM-TEMPERATURE NOTCHED TENSILE PROPERTIES OF STRESS-RELIEVED Mo-0.5Zr SHEET (0.043 INCH)[a][3]

Notch Radius, inch	Notch Width, inch	K_t	Notched Tensile Strength, 1000 psi	Elongation in 3/4 Inch, per cent	Notched Tensile/ Unnotched Tensile Strength Ratio
0.012	0.427	4.4	122.0	2.0	1.14
			118.3	1.5	1.09
0.004	0.418	7.3	116.0	2.5	1.07
			116.8	2.0	1.07

(a) Stress relieved 1 hour at 2200 F. Test rate 0.005 inch per inch per minute to yielding, then 0.03 inch per inch per minute to fracture. Nominal carbon content 0.04 per cent.

TABLE A-39. CREEP AND STRESS-RUPTURE PROPERTIES OF STRESS-RELIEVED AND RECRYSTALLIZED Mo-0.5Zr AT 1800 AND 2400 F[a][4]

Condition	Temperature, F	Stress, 1000 psi	Creep Rate, per cent/hour	Rupture Time, hours	Elongation, per cent	Reduction in Area, per cent
Stress relieved	1800	70.0	--	0	8.3	24.9
		60.0	0.085	53.8	20.0	84.9
	2400	20.0	--	0	5.2	15.3
		15.0	1.10	3.1	5.9	10.8
Recrystallized	1800	40.0	5.00	3.1	39.2	89.4
		35.0	0.41	42.2	28.2	80.6
	2400	12.5	--	37.6	--	--
		10.0	0.12	37.3	14.8	23.0

(a) Analyses 0.49% Zr and 0.022% C.

TABLE A-40. STRESS-RUPTURE PROPERTIES OF STRESS-RELIEVED Mo-0.5Zr SHEET (0.040 INCH) AT 2200 AND 2500 F[a][3]

Temperature, F	Stress, 1000 psi	Time to Rupture, hours	Elongation, per cent
2200	37.0	1.64	12
	32.0	19.2	15
	30.0	7.4	16
	30.0	8.6	5
2500	16.5	15.5	32
	12.0	65.6	36

(a) Stress relieved 1 hour at 2200 F. Nominal carbon content 0.04 per cent.

TABLE A-41. ROOM-TEMPERATURE BEND DATA FOR Mo-0.5Zr SHEET[2]

Fabrication Data					Results of 105-Deg V-Block Bend	
Method	Reduction, per cent	Test Direction	Number of Specimens Tested	Bend Radius, T	Passed	Failed (Cracked)
Vapor Blasted and Electropolished to Remove 1/2 Mil per Side						
Straight rolled	90	Longitudinal	4	2	2	2
Straight rolled	90	Transverse	4	2	0	4
Cross rolled	90	Longitudinal	4	2	1	3
Cross rolled	90	Transverse	3	2	3	0
Straight rolled	75	Longitudinal	3	2	0	3
Straight rolled	75	Transverse	4	2	1	3
Cross rolled	75	Longitudinal	2	2	0	2
Cross rolled	75	Transverse	3	2	0	3
Straight rolled	60	Longitudinal	2	2	1	1
Straight rolled	60	Transverse	2	2	2	0
Cross rolled	60	Longitudinal	2	2	2	0
Cross rolled	60	Transverse	2	2	0	2
Annealed 2200 F 1 Hour; Virgo Pickled 1-1/2 Minutes to Remove 4 to 5 Mils per Side						
Straight rolled	90	Transverse	3	2-1/2	3	0
Straight rolled	90	Transverse	1	1-1/2	0	1[a]

(a) Cracked at bottom of stroke.

4. Metallurgical Properties

a. Fabricability: the following schedule has been successfully used to convert ingot to sheet: (1) extrude at 2850 F, (2) forge extruded sheet bar at 2800 to 3000 F, (3) breakdown rolling of forged bar at 2400 to 2600 F, (4) roll to plate sizes at 2200 to 2400 F, and (5) sheet rolling at 2250 F[2]

b. Transition temperature: -60 to -20 F for bar (1/2-inch diameter) material[4]; <-40 F for sheet (0.040 inch) material[3]

c. Stress-relief temperature: 1 hour at 2200 F[3,4]

d. Recrystallization temperature: effect of annealing temperature on recrystallization and hardness of sheet material[3]

1-Hour Annealing Temperature, F	Recrystallization, per cent	Hardness, VHN
As received[a]	0	273
2400	0	281
2500	0	294
2600	95	188
2700	100	182

(a) Stress relieved 1 hour at 2200 F.

Figure A-85

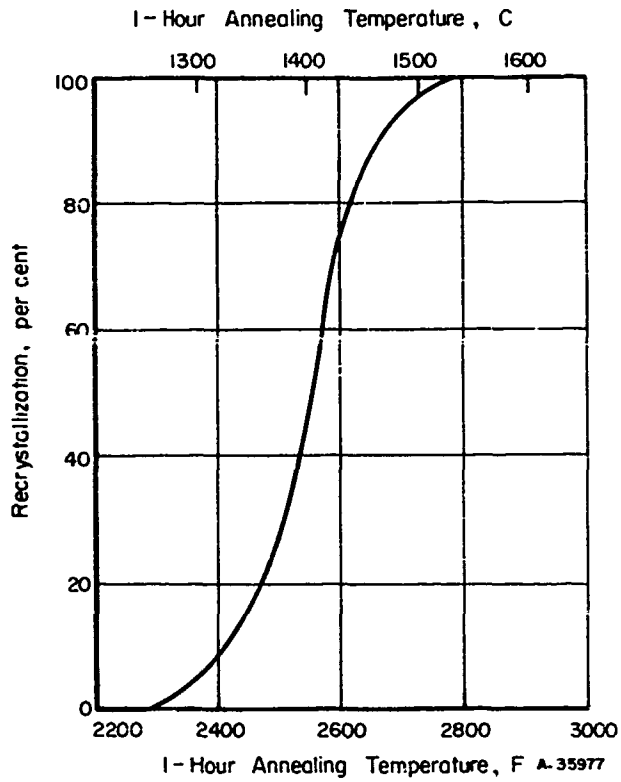


FIGURE A-85. EFFECT OF ANNEALING TEMPERATURE ON THE RECRYSTALLIZATION BEHAVIOR OF Mo-0.5 Zr[4]

References

(1) Semchyshen, M., McArdle, G. D., and Barr, R. Q., "Development of Molybdenum-Base Alloys", Climax Molybdenum Co., WADC TR 59-280 (October, 1959).

(2) Redden, T. R., "Molybdenum Alloy Sheet Studies During 1957", General Electric Co. (February 28, 1959).

(3) Neff, C. W., Frank, R. G., and Luft, L., "Refractory Metals Structual Development Program, Refractory Alloy and Coating Development", Volume II, McDonnell Aircraft Corp. and General Electric Co., ASD TR 61-392 (October, 1961).

(4) Semchyshen, M., McArdle, G. D., and Barr, R. Q., "Development of High Strengths and High Recrystallization Temperature in Molybdenum-Base Alloys, Climax Molybdenum Co., WADC TR 58-551 (February, 1959).

Mo-0.5Ti

1. Identification of Material

   a. Designation: many, depending upon individual supplier

   b. Chemical composition: Tables A-42 and A-43

   c. Forms available: billets, forgings, strip, sheet, foil, plate, bar, rod, and wire[1-4]

TABLE A-42. CHEMICAL REQUIREMENTS FOR Mo-0.5Ti PRODUCTS AS PRODUCED BY ARC-CASTING TECHNIQUES[a](1-4)

Element	Content, Maximum, weight per cent
C	0.010-0.040
O	0.0030
N	0.0010
Fe	0.020
Ni	0.010
Si	0.010
Ti	0.40-0.55
Mo	99.35 min

(a) For forgings, billets for reforging, strip, sheet, foil, plate, bar, rod, and wire.

TABLE A-43 REPRESENTATIVE ANALYSES OF Mo-0.5Ti AS PRODUCED BY VARIOUS SUPPLIERS

	Content, Maximum, weight per cent		
	Arc Cast		Powder Metallurgy
Element	Climax[a](5, 6)	Universal Cyclops[b](7-10)	Sylvania[c](11)
Al	--	0.002	0.0010
C	0.01-0.04	0.01-0.040	0.02-0.04
Ca	--	0.002	0.0010
Co	--	0.002	--
Cr	--	0.004	0.0050
Cu	--	0.002	0.0010
Fe	0.010	0.010	0.0050
H	0.0005	0.001	<0.0010 typ
K	--	0.001	--
Pb	--	0.002	0.0010
Mg	--	0.002	0.0010
Mn	--	0.002	0.0010
Mo	99.35 min	99.34 min	99.36 min
Na	--	0.001	--
N	0.002	0.001	0.0050 typ
Ni	0.002	0.002	0.0050
O	0.0025	0.003	0.0100 typ
Si	0.008	0.020	0.0050
Sn	--	0.004	0.0050
Ti	0.40-0.55	0.40-0.550	0.45-0.55
W	--	0.002	--
Zr	--	0.002	--

(a) For forging billets and wrought bars.
(b) For billets, bar, plate, and sheet.
(c) For billets.

2 Physical Properties

a. Melting point: ~4730 F (essentially the same as that for unalloyed molybdenum)

b. Density: 0.367 lb/in.^{3} (calculated)

c. Thermal expansion: Table A-44

d. Thermal conductivity: Table A-45

TABLE A-44. MEAN LINEAR THERMAL-EXPANSION COEFFICIENT OF Mo-0.5Ti[12]

Temperature Range, F	Mean Coefficient of Thermal Expansion, 10^{-6}/F
68-212	3.05
68-392	3.06
68-572	3.09
68-752	3.14
68-932	3.19
68-1112	3.24
68-1292	3.28
68-1472	3.32
68-1652	3.36
68-1832	3.41

TABLE A-45. INTERPOLATED THERMAL-COND[illegible] FOR Mo-0.5Ti[12]

Temperature, F	Th[illegible]
68	
212	
392	
572	
752	[illegible]
932	[illegible]7
1112	63.57
1292	63.57
1472	62.99
1652	62.41

3. Mechanical Properties

a. Tensile Properties at Room Temperature

Ultimate tensile strength: Tables A-46 through A-53
Figures A-86 and A-87

Tensile yield strength: Tables A-46 through A-53
Figure A-87

Elongation: Tables A-46 through A-53
Figures A-86 and A-87

Reduction in area: Table A-53
Figure A-86

Modulus of elasticity: 46×10^6 psi[23]

b. Effect of Temperature on Tensile Properties

Ultimate tensile strength: Tables A-54 through A-
Figures A-88 through A-94

Tensile yield strength: Tables A-54 through A-56
Figures A-88 and A-89 and A-91 through A-94

Elongation: Tables A-54 through A-56
Figures A-88 through A-91 and A-94

Reduction in area: Table A-54
Figures A-88 through A-90

Modulus of elasticity: Tables A-54 and A-57

c. Notched Tensile Properties

Figures A-95 through A-103

d. Creep and Stress-Rupture Properties

Tables A-58 through A-63
Figures A-104 through A-106

e. Other Selected Mechanical Properties

Hardness: Table A-64
Figure A-107

Bend ductility: Tables A-65 and A-66
Figure A-108

Compressive strength: Tables A-67 and A-68

Shear strength: data at room temperature and 1600 F have been determined for fastener material(39)

Type Fastener	Diameter, inch	Shear Strength, 1000 psi	
		RT	1600 F
Cr coated rivet	0.136	57.5	50.0
		58.0	49.0

Table A-69

Fatigue strength: Figure A-109

TABLE A-46. TENSILE-PROPERTY REQUIREMENTS FOR ARC-CAST Mo-0.5Ti ROUND RODS[a][4]

Condition	Diameter, inches	Minimum Tensile Strength, 1000 psi	Minimum Yield Strength (0.2% Offset), 1000 psi	Minimum Elongation in 1 Inch, per cent
Stress relieved	3/16 to 7/8, incl.	105	90	10
	Over 7/8 to 1-1/8	100	85	8
	Over 1-1/8 to 1-7/8	90	75	5
	Over 1-7/8 to 2-7/8	80	70	4
	Over 2-7/8 to 3-1/2	75	65	3
Recrystallized	Under 2	70	40	15
	2 to 3-1/2	65	30	8

(a) Properties shall be determined using a test rate of 0.002 to 0.005 inch per inch per minute through 0.6 per cent offset, then 0.02 to 0.05 inch per inch per minute to fracture.

TABLE A-47. TENSILE-PROPERTY REQUIREMENTS FOR ARC-CAST Mo-0.5Ti STRIP, SHEET, FOIL, AND PLATE[a][3]

Tensile-Strength Range, 1000 psi	Minimum Yield Strength (0.2% Offset, 1000 psi	Minimum Elongation in 2 Inches, per cent: Specimens Equal to or Less Than 0.020 In. Thick	Minimum Elongation in 2 Inches, per cent: Specimens Greater Than 0.020 In. Thick
70-100	55	5	10
100-130	80	5	7
130-160	100	4	5
160-190	120	2	5

(a) Properties shall be determined using a test rate of 0.002 to 0.005 inch per inch per minute through 0.6 per cent offset, then 0.02 to 0.05 inch per inch per minute to fracture.

TABLE A-48. TYPICAL ROOM-TEMPERATURE TENSILE DATA FOR ARC-CAST STRESS-RELIEVED Mo-0.5Ti ROUND BAR PRODUCED BY CLIMAX[a][13]

Diameter, inches	Average Tensile Strength, 1000 psi	Average Yield Strength (0.2% Offset), 1000 psi	Average Elongation in 1 Inch, per cent
1/2	110	106	29
5/8	116	116	26
3/4	115	102	25
7/8	123	108	28
1	116	97	23
1-1/8	109	95	15
1-1/2	103	91	20
2	96	84	20
2-1/4	92	80	15
2-3/8	92	82	15
2-1/2	90	80	9
3	89	79	15

(a) Cold Water Production Facility. All data from 6-inch-diameter arc-cast ingots covering a 3-year period. Material stress relieved 1/4 to 1-1/2 hours at 2000 to 2150 F. Test rate 0.002 inch per inch per minute in the elastic range, then 0.05 inch per inch per minute to fracture.

TABLE A-49. ROOM-TEMPERATURE TENSILE PROPERTIES OF UNIVERSAL CYCLOPS ARC-CAST Mo-0.5Ti PLATE AND SHEET PRODUCTS[a][9,10]

Property	Minimum	Typical
Plate, Over 3/16 Inch to 1/2 Inch		
Tensile Strength, 1000 psi	100	110
Yield Strength (0.2% Offset), 1000 psi	90	100
Elongation in 2 Inches, per cent	4	8
Plate, Over 1/2 Inch to 1-1/2 Inches		
Tensile Strength, 1000 psi	95	105
Yield Strength (0.2% Offset), 1000 psi	85	95
Elongation in 2 Inches, per cent	3	6
Sheet, 0.020 Inch and Under		
Tensile Strength, 1000 psi	110	125
Yield Strength (0.2% Offset), 1000 psi	100	115
Elongation in 2 Inches, per cent	6	8
Sheet, Over 0.020 Inch		
Tensile Strength, 1000 psi	105	130
Yield Strength (0.2% Offset), 1000 psi	95	120
Elongation in 2 Inches, per cent	8	10

(a) Test rate 0.05 inch per inch per minute crosshead speed.

TABLE A-50. ROOM-TEMPERATURE TENSILE PROPERTIES OF SYLVANIA POWDER METALLURGY Mo-0.5Ti SHEET (0.040 INCH)[11]

Condition	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation, per cent
As rolled	150	140	7
Recrystallized	80	67	32

TABLE A-51. STATISTICAL EVALUATION OF THE ROOM-TEMPERATURE TENSILE PROPERTIES OF ARC-CAST Mo-0.5Ti SHEET SUPPLIED BY UNIVERSAL CYCLOPS[a](14)

Gage, inch	No. of Sheets	No. of Specimens, n	Grain Direction	Arithmetic Mean, $\bar{x} = \frac{\Sigma x}{n}$	Standard Deviation, σ	Deviation From the Mean Property Indicated		
						$\bar{x} \pm \sigma$ (b)	$\bar{x} \pm 2\sigma$ (c)	$\bar{x} \pm 3\sigma$ (d)
				Tensile Strength, 1000 psi				
0.012	43	43	Long.	129.1	7.6	121.5-136.6	113.9-144.2	106.4-151.7
		85	Trans.	139.0	8.8	130.2-147.8	121.4-156.6	112.6-165.4
0.020	18	18	Long.	127.9	2.4	125.5-130.3	123.1-132.7	120.7-135.1
		36	Trans.	132.7	4.4	128.3-137.1	123.9-141.5	119.5-145.9
0.030	30	30	Long.	135.4	5.4	130.0-140.8	124.6-146.2	119.2-151.6
		60	Trans.	142.1	6.1	136.0-148.2	129.9-154.3	123.8-160.4
0.040	11	11	Long.	129.7	2.6	127.1-132.3	124.5-134.9	121.9-137.5
		22	Trans.	136.5	3.7	132.8-140.2	129.1-143.9	125.4-147.6
0.050	21	21	Long.	132.1	3.4	128.7-135.5	125.3-138.9	121.9-142.3
		39	Trans.	129.0	3.7	135.3-142.7	131.6-146.4	127.9-150.1
				Yield Strength (0.2% Offset), 1000 psi				
0.012	43	43	Long.	114.4	8.0	106.4-122.4	98.4-130.4	90.4-138.4
		85	Trans.	124.8	9.6	115.2-134.9	105.6-144.0	96.0-153.6
0.020	18	18	Long.	113.8	2.8	111.0-116.6	108.2 119.4	105.4-122.2
		36	Trans.	121.0	5.0	116.0-126.0	111.0-131.0	106.0-136.0
0.030	30	30	Long.	119.3	6.0	113.3 125.3	107.3-131.3	101.3-137.3
		60	Trans.	127.3	5.5	122.4-133.2	117.0-138.6	111.6-144.0
0.040	11	11	Long.	116.5	1.8	114.7-118.3	112.9-120.1	111.1-121.9
		22	Trans.	124.9	2.5	122.4-127.4	119.9-129 9	117.4-132.4
0.050	21	21	Long.	117.2	4.9	112.3-122.1	107.4-127.0	102.5-131.9
		39	Trans.	127.9	4.8	123.1-132.7	118.3-137.5	113.5-142.3
				Elongation in 2 Inches, per cent				
0.012	43	43	Long.	10.6	2.7	7.9-13.3	5.2-16.0	3.5-18.7
		85	Trans.	6.9	2.3	4.6-9.2	2.3-11.5	0.0-13.8
0.020	18	18	Long.	15.2	1.9	13.3-17.1	11.4-19.0	9.5-20.9
		36	Trans.	11.6	2.2	9.4-13.8	7.2-16.0	5.0-18.2
0.030	30	30	Long.	13.0	2.3	10.7-15.3	8.4-17.6	6.1-19.9
		60	Trans.	10.2	2.5	7.7-12.7	5.2-15.2	2.7-17.7
0.040	11	11	Long.	16.1	1.3	14.8-17.4	13.5-18.7	12.2-20.0
		22	Trans.	11.6	1.4	10.2-13.0	8.8-14.4	7.4-15.8
0.050	21	21	Long.	16.2	1.5	14.7-17.7	13.2-19.2	11.7-20.7
		39	Trans.	11.5	1.5	10.0-13.0	8.5-14.5	7.0-16.0

Footnotes appear on the following page.

Footnotes for Table A-51:

(a) Test rate 0.005 ± 0.002 inch per inch per minute to 0.6 per cent offset, then 0.1 ± 0.02 inch per inch per minute to fracture. Chemical analyses 0.31-0.50% Ti, 0.011-0.035% C (70% were below 0.025% C), 0.0004% H max, and 0.0011% N. The following definitions apply:

n = The number of specimens tested

x = The tensile strength, yield strength, or elongation of each specimen tested

$\sigma = \sqrt{\frac{\Sigma(\bar{x}-x)^2}{n}}$ = one standard deviation.

(b) The tensile strength, yield strength, or elongation of 68 per cent of the specimens tested lies within the range of $\bar{x} \pm \sigma$.

(c) The tensile strength, yield strength, or elongation of 95 per cent of the specimens tested lies within the range of $\bar{x} \pm 2\sigma$.

(d) The tensile strength, yield strength, or elongation of 99.7 per cent of the specimens tested lies within the range of $\bar{x} \pm 3\sigma$.

TABLE A-52. STATISTICAL EVALUATION OF THE ROOM-TEMPERATURE TENSILE PROPERTIES OF ARC-CAST Mo-0.5Ti SHEET SUPPLIED BY FANSTEEL[a][14]

Gage, inch	No. of Sheets	No. of Specimens, n	Grain Direction	Arithmetic Mean, $\bar{x} = \frac{\sum x}{n}$	Standard Deviation, σ	Deviation From the Mean Property Indicated		
						$\bar{x} \pm \sigma$[b]	$\bar{x} \pm 2\sigma$[c]	$\bar{x} \pm 3\sigma$[d]
				Tensile Strength, 1000 psi				
0.012	42	42	Long.	109.1	21.0	88.1-130.1	67.1-151.1	46.1-172.1
		84	Trans.	119.4	26.5	92.9-145.9	66.4-172.4	39.9-198.9
0.020	6	6	Long.	143.2	3.8	139.4-147.0	135.6-150.8	131.8-154.6
		12	Trans.	155.4	5.6	149.8-161.0	144.2-166.6	138.6-172.2
0.030	21	21	Long.	128.1	5.1	123.0-133.2	117.9-138.3	112.8-143.4
		42	Trans.	140.8	3.8	137.0-144.6	133.2-148.4	129.4-152.2
0.040	17	17	Long.	129.3	1.1	128.2-130.4	127.1-131.5	126.0-132.6
		34	Trans.	127.8	3.5	135.9-140.5	133.6-142.8	131.3-145.1
0.050	13	13	Long.	130.7	4.8	125.9-135.5	121.1-140.3	116.3-145.1
		26	Trans.	138.8	5.1	133.7- 43.9	128.6-149.0	123.5-154.1
				Yield Strength (0.2% Offset), 1000 psi				
0.012	42	42	Long.	84.2	24.4	59.8-108.6	35.3-133.0	10.9-157.5
		84	Trans.	98.9	31.6	67.5-130.3	36.1-193.1	4.7-224.5
0.020	6	6	Long.	126.2	4.1	122.1-130.3	118.0-134.4	113.9-138.5
		12	Trans.	141.9	6.3	135.6-148.2	129.3-154.5	123.0-160.8
0.030	21	21	Long.	117.1	10.3	106.8-127.4	96.5-137.7	86.2-148.0
		42	Trans.	132.1	5.0	127.1-137.1	122.1-142.1	117.1-147.1
0.040	17	17	Long.	114.3	2.2	112.1-116.5	109.9-118.7	107.7-120.9
		34	Trans.	127.8	3.5	124.3-131.3	120.8-134.8	117.3-138.3
0.050	13	13	Long.	113.6	6.1	107.5-119.7	101.4-125.8	95.3-131.9
		26	Trans.	125.8	5.3	120.5-131.1	115.2-136.4	109.9-141.7
				Elongation in 2 Inches, per cent				
0.012	42	42	Long.	15.9	6.7	9.2-22.6	2.5-29.3	0.0-36.0
		84	Trans.	14.3	7.8	6.5-22.1	0.0-29.9	0.0-37.7
0.020	6	6	Long.	11.6	1.5	10.1-13.1	8.6-14.6	7.1-16.1
		12	Trans.	6.6	1.9	4.7-8.5	2.8-10.4	0.9-12.3
0.030	21	21	Long.	12.0	1.6	10.4-13.6	8.8-15.2	7.2-16.8
		42	Trans.	9.5	1.5	8.0-11.0	6.5-12.5	5.0-14.0
0.040	17	17	Long.	14.6	1.1	13.5-15.7	12.4-16.8	11.3-17.9
		34	Trans.	10.6	1.7	8.9-12.3	7.2-14.0	5.5-15.7
0.050	13	13	Long.	16.9	4.8	12.1-21.7	7.3-26.5	2.5-31.3
		26	Trans.	12.4	4.4	8.0-16.8	3.6-21.2	0.0-25.6

Footnotes appear on the following page.

Footnotes for Table A-52:

(a) Test rate 0.005 ± 0.002 inch per inch per minute to 0.6 per cent offset, then 0.1 ± 0.02 inch per inch per minute to fracture. Chemical analyses 0.39-0.54% Ti, 0.002-0.042% C (84% were below 0.025% C), 0.0007% H max, 0.0187% O max, and 0.0025% N. The following definitions apply:

n = the number of specimens tested

x = the tensile strength, yield strength, or elongation of each specimen tested

$\sigma = \sqrt{\frac{\Sigma(\bar{x}-x)^2}{n}}$ = one standard deviation.

(b) The tensile strength, yield strength, or elongation of 68 per cent of the specimens tested lies within the range of $\bar{x} \pm \sigma$.

(c) The tensile strength, yield strength, or elongation of 95 per cent of the specimens tested lies within the range of $\bar{x} \pm 2\sigma$.

(d) The tensile strength, yield strength, or elongation of 99.7 per cent of the specimens tested lies within the range of $\bar{x} \pm 3\sigma$.

TABLE A-53. SOME SELECTED ROOM-TEMPERATURE TENSILE PROPERTIES OF Mo-0.5Ti ROD, BAR, AND SHEET

Condition	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation, per cent	Reduction in Area, per cent	Reference
		Rod and Bar			
Rod (0.375 inch)					
0% rex	114.6	92.4	36.5	38.8	(15)
5.1% rex	104.9	85.1	37.3	62.5	(15)
34.9% rex	94.1	67.7	35.3	49.4	(15)
46.3% rex	86.6	55.5	46.0	55.8	(15)
63.5% rex	82.9	51.6	40.0	42.5	(15)
74.4% rex	81.7	49.2	41.3	66.6	(15)
97.6% rex	74.4	48.6	--	--	(15)
100% rex	74.4	53.1	49.3	38.5	(15)
Rod (rolled 2250 F, 0.375 inch)					
As rolled, forged 1800 F	105.3	94.5	--	--	(15)
As rolled, forged 2100 F	111.5	96.3	--	--	(15)
As rolled, forged 2400 F	95.5	89.6	--	--	(15)
50% rex, forged 1800 F	91.4	76.8	--	--	(15)
50% rex, forged 2100 F	93.2	92.6	--	--	(15)
50% rex, forged 2400 F	96.5	94.2	--	--	(15)
100% rex, forged 1800 F	84.8	78.6	--	--	(15)
100% rex, forged 2100 F	86.5	83.3	--	--	(15)
100% rex, forged 2400 F	90.0	88.9	--	--	(15)
Rod (rolled 2400 F, 0.375 inch)					
As rolled, forged 1800 F	107.8	93.3	--	--	(15)
As rolled, forged 2100 F	106.0	91.7	--	--	(15)
As rolled, forged 2400 F	92.4	--	--	--	(15)
50% rex, forged 1800 F	90.0	81.4	--	--	(15)
50% rex, forged 2100 F	94.8	81.6	--	--	(15)
50% rex, forged 2400 F	92.9	88.2	--	--	(15)
100% rex, forged 1800 F	84.3	71.6	--	--	(15)
100% rex, forged 2100 F	88.4	82.3	--	--	(15)
100% rex, forged 2400 F	89.9	88.6	--	--	(15)
Rod (0.375 inch)					
Rolled 6.2% at 1800 F	77.7	57.0	32.7	35.7	(15)
Rolled 17.1% at 1800 F	81.8	68.1	30.0	30.7	(15)
Rolled 33.8% at 1800 F	89.1	75.9	24.0	28.7	(15)
Rolled 81.9% at 1800 F	113.8	101.3	28.7	43.4	(15)
Rolled 7.2% at 2100 F	79.6	69.5	32.0	27.7	(15)
Rolled 17.3% at 2100 F	83.0	71.1	28.7	28.7	(15)
Rolled 81.3% at 2100 F	109.1	92.5	32.7	32.7	(15)
Rolled 6.7% at 2400 F	78.5	70.2	34.0	27.0	(15)
Rolled 17.1% at 2400 F	86.9	75.2	16.0	25.5	(15)
Rolled 82.2% at 2400 F	97.2	80.8	37.3	44.8	(15)
Recrystallized rod (7/16 inch)[a]	91	91	35	31.2	(16)

TABLE A-53. (Continued)

Condition	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation, per cent	Reduction in Area, per cent	Reference
		Rod and Bar (Continued)			
Bar (1/2 inch square)					
Rolled 16.1% at 1800 F	81.2	65.7	38	31.7	(17)
Rolled 47.6% at 1800 F	99.7	87.0	37	66.4	(17)
Rolled 4.7% at 2200 F	77.1	56.5	45	43.1	(17)
Rolled 8.3% at 2200 F	78.9	66.1	42	33.9	(17)
Rolled 13.3% at 2200 F	78.9	67.8	34	31.2	(17)
Rolled 17.5% at 2200 F	84.5	70.7	40	35.9	(17)
Rolled 27.2% at 2200 F	87.9	73.2	39	39.3	(17)
Rolled 49.0% at 2200 F	102.2	92.5	25	37.8	(17)
Rolled 79.5% at 2200 F	114.4	103.9	34	66.6	(17)
Stress-relieved rod (5/8 inch)[b]	112.9	103.4	36	62.1	(18)
	111.4	104.6	39	66	(18)
As rolled rod (3/8 inch)	101.85	101.85	16.7	20.4	(17)
	103.25	103.25	21.7	26.7	(17)
Rod (5/8 inch)[c]					
As rolled	120.8	87.9[d]	33	66.4	(19)
Stress relieved	119	87.6[d]	36	66.5	(19)
Recrystallized	77.5	63.7[d]	36	34.8	(19)
As rolled	112.9	96.7[d]	29	59.7	(18)
Stress relieved	132.1	99.1[d]	31	70	(18)
		Sheet			
Stress-relieved sheet (0.065 inch)[e]	126.1	108.2	21	37.2	(16)
	129.4	106.8	22	38.4	(16)
Recrystallized sheet (0.065 inch)[e]	84.9	84.9	58	63.5	(16)
	89.5	83.5	46	60.4	(16)
Recrystallized sheet[e]					
As-rolled surface	126.6 (L)	125.3 (L)	0.24 (L)	--	(20)
	117.1 (T)	110.4 (T)	0.88 (T)	--	(20)
	116.7 (T)	108.7 (T)	0.88 (T)	--	(20)
Surface ground	132.2 (L)	124.4 (L)	4.1 (L)	--	(20)
	135 (L)	125 (L)	6.2 (L)	--	(20)
	120 (T)	103.7 (T)	14.8 (T)	--	(20)
	119.2 (T)	106.2 (T)	12 (T)	--	(20)
Sheet (1/16 inch)					
As rolled, 272 VHN[f]	91.6 (L)	79.4 (L)	10 (L)	--	(21)
	110.5 (T)	86.3 (T)	8 (T)	--	(21)
Stress relieved, 266 VHN[f]	85.1	80.8	1	--	(21)

TABLE A-53. (Continued)

Condition	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation, per cent	Reduction in Area, per cent	Reference
		Sheet (Continued)			
Sheet (1/16 inch) (Continued)					
Recrystallized, 194 VHN[f]	81 (L)	68 (L)	28 (L)	--	(21)
	66 (T)	58.5 (T)	3 (T)	--	(21)
As rolled, 309 VHN[g]	135.1	107.3	13	--	(21)
Stress relieved, 300 VHN[g]	114.1	90.2	16	--	(21)
Recrystallized, 197 VHN[g]	74	52	34	--	(21)
As rolled, 302 VHN[h]	125.9 (L)	115.9 (L)	1 (L)	--	(21)
	126.4 (T)	121.3 (T)	0.5 (T)	--	(21)
Stress relieved, 285 VHN[b]	97.5 (L)	96.4 (L)	1 (L)	--	(21)
	122.1 (T)	116.5 (T)	1 (T)	--	(21)
Recrystallized, 192 VHN[b]	58.5 (L)	57.9 (L)	0.5 (L)	--	(21)
	55.8 (T)	55.8 (T)	0.5 (T)	--	(21)
As rolled, 264 VHN[b]	101.4 (L)	80.6	1	--	(21)
	89.6 (T)	--	0	--	(21)
Stress relieved, 247 VHN[i]	73.0 (T)	--	0 (T)	--	(21)
Recrystallized, 193 VHN[i]	36.7 (L)	--	0 (L)	--	(21)
	48.9 (T)	43.8 (T)	1 (T)	--	(21)

(a) 0.46% Ti and 0.012% C.
(b) 0.46% Ti and 0.023% C.
(c) 0.46% Ti and 0.021% C.
(d) 0.1 per cent offset.
(e) 0.47% Ti and 0.02% C.
(f) 0.023% C.
(g) 0.019% C.
(h) 0.046% C.
(i) 0.047% C.

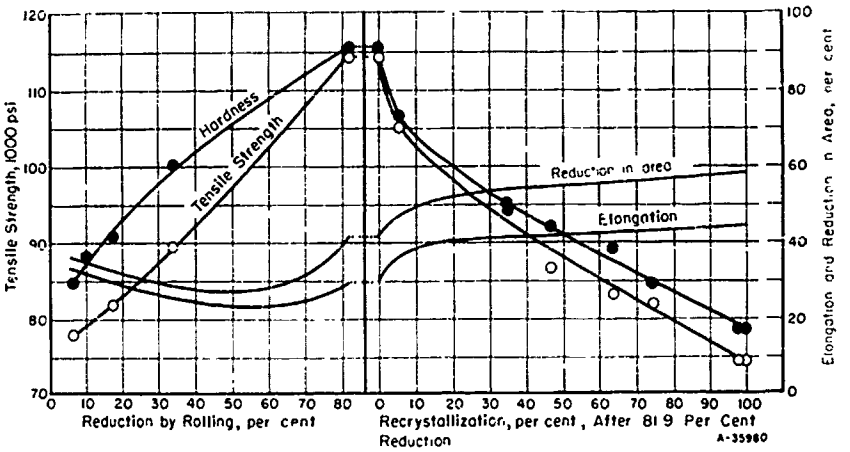


FIGURE A-86. ROOM-TEMPERATURE HARDNESS AND TENSILE PROPERTIES OF Mo-0.5Ti BAR (3/4-INCH SQUARE)[15]

Rolled at 1800 F.

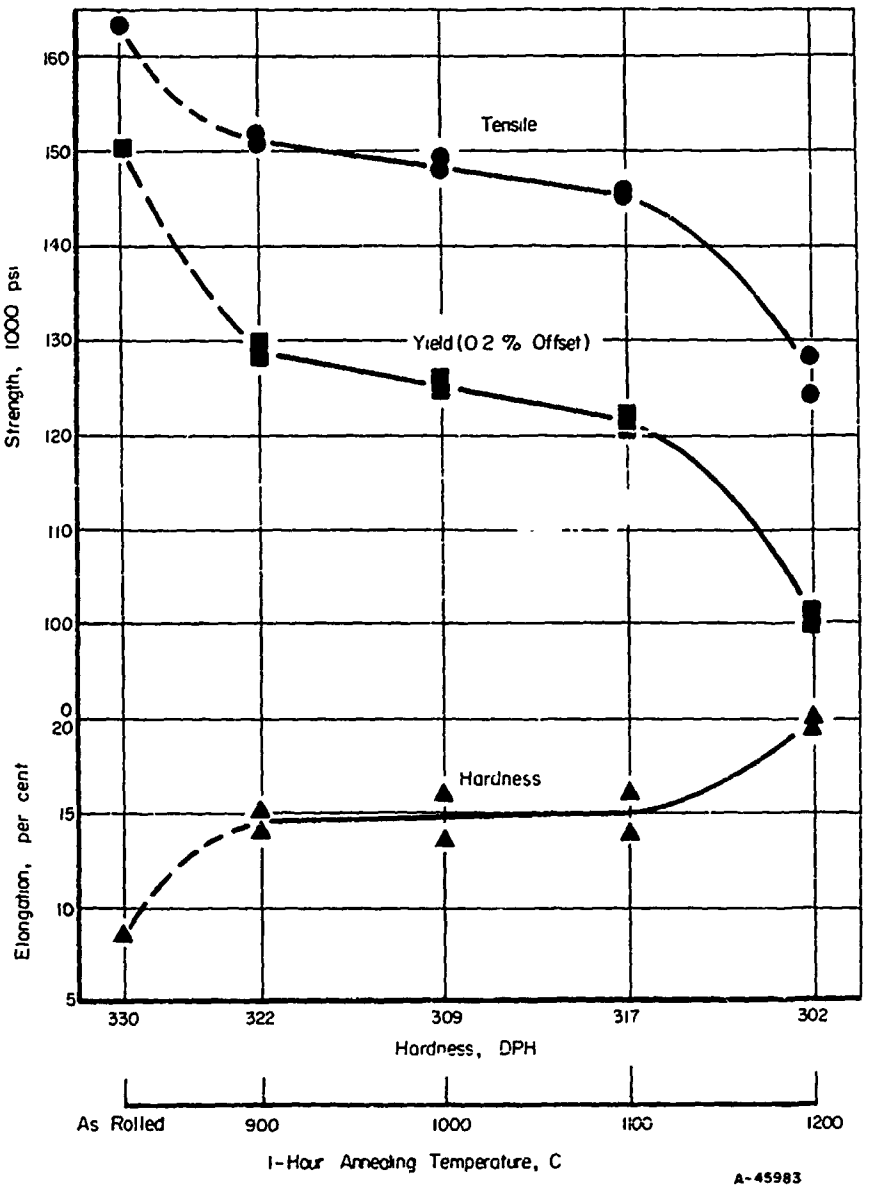


FIGURE A-67. EFFECT OF ANNEALING TEMPERATURE ON THE ROOM-TEMPERATURE TENSILE PROPERTIES OF SYLVANIA POWDER-METALLURGY Mo-0.5Ti SHEET (0.040 INCH)[22]

TABLE A-54. EFFECT OF TEMPERATURE AND STRAIN RATE ON THE TENSILE PROPERTIES OF RECRYSTALLIZED ARC-CAST Mo-0.5Ti BAR AND SHEET IN ARGON[a][24]

Temperature, F	Strain Rate, in./in./min	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation in 2 Inches, per cent	Modulus of Elasticity, 10^6 psi
		Bar, 3/8-Inch Diameter			
RT	0.002	77.1	65.0/54.1[b]	34.0	55.7
	0.2	80.0	71.5/68.5[b]	35.5	17.9
1200	0.002	39.2	15.5	38.8	13.0
	0.2	35.8	--	44.5	--
2100	0.002	22.0	13.2	22.0	12.5
	0.2	31.3	--	30.0	--
2600	0.002	13.8	10.2	21.8	15.0
	0.2	11.5	9.1	22.0	14.6
3000	0.002	4.24	--	25.0	--
	0.2	6.76	4.26	25.5	2.12
		Sheet, 0.060 Inch			
RT	0.002	76.9	61.5/47.1[b]	21.0	43.4
	0.2	78.5	68.4/67.8[b]	20.0	43.5
1200	0.002	37.1	12.95	30.0	22.8
	0.2	35.0	9.32	30.2	19.0
2100	0.002	31.9	13.6	12.5	23.8
	0.2	33.2	13.18	20.0	19.0
2600	0.002	12.27	11.02	11.0	10.2
	0.2	16.32	9.10	13.5	6.9
3000	0.002	2.84	--	12.0	--
	0.2	5.20	--	16.2	--

(a) Recrystallized 35 minutes at 2900 F, ASTM 6.
(b) Upper yield strength/lower yield strength.

TABLE A-55. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF AS-ROLLED POWDER-METALLURGY Mo-0.5Ti SHEET (0.040 INCH)[11]

Temperature, F	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation, per cent
RT	150	140	7
2000	78	61	10
2200	55	38	10
2400	28	21	20

TABLE A-56. EFFECT OF TEMPERATURE ON SOME SELECTED TENSILE PROPERTIES OF Mo-0.5Ti ROD, BAR, AND SHEET

Condition	Temperature, F	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation, per cent	Reduction in Area, per cent	Reference
		Rod and Bar				
Rod (7/16 inch)[a]						
Stress relieved	-165	190.3	190.3	--	--	(16)
	-165	184.6	184.6	--	--	(16)
Recrystallized	-105	120	120	--	0	(16)
	-105	121.9	121.9	--	0	(16)
Stress relieved	-75	157.4	157.4	26	69	(16)
	-75	154	153.5	21	64.6	(16)
Stress relieved	32	136.2	134.6	25	67.8	(16)
	32	137.2	134.2	22	69	(16)
Recrystallized	32	103	103	--	10.3	(16)
Rod (7/16 inch)[a]						
Stress relieved	212	107.6	104	34	77.4	(16)
	212	105.6	104.2	27	78.1	(16)
Recrystallized	212	71.5	71.5	--	30.5	(16)
	212	66.3	66.3	33	34.6	(16)
As-rolled rod (3/8 inch)	300	73.9	69.6	25.6	61.4	(25)
	300	73.35	68.75	29.5	66.9	(25)
Recrystallized rod (7/16 inch)[a]	570	49.7	45.5	49	85	(16)
Rod (3/8 inch)						
As rolled	570	67.45	65.1	29	74.7	(17)
	570	67.9	65.5	25.6	78.7	(17)
	750	100.4	78.9[b]	18	76.1	(18)
Stress relieved	750	110.0	89[b]	18	72.8	(18)
Recrystallized	750	45.6	30.2[b]	47	86.4	(17)
Rod (1 inch)						
As rolled	750	90.8	--	16	75.5	(17)
Stress relieved	750	90.7	71.4[b]	17	73.5	(17)
Recrystallized	750	42.4	16.8[b]	45	83.9	(17)
As-rolled rod (3/8 inch)	930	62.65	61.5	22.7	84.2	(25)
	930	61.1	60	24	82.7	(25)
	1110	65.4	65.25	20.4	82.1	(25)
	1110	57.5	55.05	26.3	84.6	(25)
Rod (5/8 inch)						
As rolled	1200	101.3	80.6[b]	18	82.6	(18)
Stress relieved	1200	100.5	84[b]	17	74.1	(18)
Recrystallized	1200	43.7	--	45	86.2	(18)

TABLE A-56. (Continued)

Condition	Temperature, F	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation, per cent	Reduction in Area, per cent	Reference
		Rod and Bar (Continued)				
Rod (1 inch)						
As rolled	1200	84.9	68.3[b]	15.5	74.5	(26)
Stress relieved	1200	84.7	62.6[b]	16	71.9	(26)
Recrystallized	1200	39.2	10.3[b]	42.5	87.7	(26)
Rod (5/8 inch)						
As rolled	1600	81.3	55.5[b]	18	79.6	(17)
Stress relieved	1600	83.2	54.5	18	76	(17)
Recrystallized	1600	39.6	13.9	50	89.9	(17)
Rod (1 inch)						
As rolled	1600	78.4	64.8[b]	15.5	75	(17)
Stress relieved	1600	77.7	62.8[b]	16	75.7	(17)
Recrystallized	1600	37.5	14.5[b]	48.5	87.6	(17)
Rod (0.300 inch)						
0% rex	1800	68.9	--	18.0	81.0	(15)
5.1% rex	1800	61.2	--	18.7	87.9	(15)
39.9% rex	1800	46.1	--	26.7	91.0	(15)
46.3% rex	1800	39.4	--	31.3	91.4	(15)
63.5% rex	1800	36.2	--	39.3	89.3	(15)
74.4% rex	1800	35.5	--	48.7	91.8	(15)
97.6% rex	1800	32.1	--	60.7	93.8	(15)
100% rex	1800	30.7	--	56.7	86.0	(15)
Rolled 6.2%, 1800 F	1800	35.8	--	53.5	92.4	(15)
Rolled 17.1%, 1800 F	1800	41.5	--	32.7	89.9	(15)
Rolled 33.8%, 1800 F	1800	48.4	--	22.0	88.4	(15)
Rolled 81.9%, 1800 F	1800	65.0	--	24.7	87.0	(15)
Rolled 7.2%, 2100 F	1800	35.0	--	50.0	91.9	(15)
Rolled 17.3%, 2100 F	1800	42.1	--	32.7	91.7	(15)
Rolled 81.3%, 2100 F	1800	65.1	--	25.3	83.5	(15)
Rolled 6.7%, 2400 F	1800	38.3	--	33.3	91.6	(15)
Rolled 17.1%, 2400 F	1800	43.7	--	30.0	90.6	(15)
Rolled 82.2%, 2400 F	1800	53.5	--	25.3	88.3	(15)
Rod (rolled 2250 F, 0.375 inch)						
As rolled, forged 1800 F	1800	64.6	--	--	--	(15)
As rolled, forged 2100 F	1800	67.8	--	--	--	(15)
As rolled, forged 2400 F	1800	46.0	--	--	--	(15)
50% rex, forged 1800 F	1800	43.7	--	--	--	(15)
50% rex, forged 2100 F	1800	43.4	--	--	--	(15)
50% rex, forged 2400 F	1800	40.9	--	--	--	(15)
100% rex, forged 1800 F	1800	36.8	--	--	--	(15)
100% rex, forged 2100 F	1800	39.0	--	--	--	(15)
100% rex, forged 2400 F	1800	39.9	--	--	--	(15)

TABLE A-56. (Continued)

Condition	Temperature, F	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation, per cent	Reduction in Area, per cent	Reference
		Rod and Bar (Continued)				
Rod (rolled 2400 F, 0.375 incl.)						
As rolled, forged 1800 F	1800	63.7	--	--	--	(15)
As rolled, forged 2100 F	1800	62.8	--	--	--	(15)
As rolled, forged 2400 F	1800	41.2	--		--	(15)
50% rex, forged 1800 F	1800	36.8	--	--	--	(15)
50% rex, forged 2100 F	1800	39.7	--	--	--	(15)
50% rex, forged 2400 F	1800	42.6	--	--	--	(15)
100% rex, forged 1800 F	1800	34.4	--	--	--	(15)
100% rex, forged 2100 F	1800	37.0	--	--	--	(15)
100% rex, forged 2400 F	1800	38.1	--	--	--	(15)
Rod (1/4 inch)[c]						
As rolled	1800	81.3	55.5	18	79.6	(21)
Stress relieved	1800	83.2	54.5	18	76.0	(21)
Recrystallized	1800	39.6	13.9	56	89.9	(21)
Rod (5/8 inch)[d]						
Stress relieved	1800	67.8	67.3	20	79.5	(17)
Stress relieved	1800	67.2	60.1	18	79.2	(17)
Stress relieved	1800	64.6	--	-	--	(27)
Stress relieved	1800	67.8	--	--	--	(27)
Stress relieved	1800	46.0	--	--	--	(27)
50% rex	1800	43.7	--	--	--	(27)
50% rex	1800	43.4	--	--	--	(27)
50% rex	1800	40.9	--	--	--	(27)
Recrystallized	1800	34.4	--	--	--	(27)
Recrystallized	1800	37	--	--	--	(27)
Recrystallized	1800	38.1	--	--	--	(27)
Stress relieved	2000	58.7	50.5	15	88.1	(17)
	2000	60.0	53.7	18	81.1	(17)
Stress relieved	2400	18.6	8.5	70	94.6	(17)
	2400	18.3	8.4	61	94.6	(17)
Rod (1/4 inch)[c]						
Stress relieved	2400	20.0	9.9	71	97.3	(21)
Recrystallized	2400	20.0	11.8	72	95.5	(21)
Bar (1/2 inch)						
Extruded, as rolled	2500	22.5	--	--	--	(25)
Recrystallized[e]	2500	24.4	--	--	75	(28)
Extruded, as rolled	2750	14.65	--	--	--	(25)
Extruded, as rolled	3000	9.8	--	56	--	(25)
Recrystallized[e]	3000	8.4	--	-	96	(28)
Recrystallized[e]	3250	4.15	--	--	99	(28)

TABLE A-56. (Continued)

Condition	Temperature F	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation, per cent	Reduction in Area, per cent	Reference
		Rod and Bar (Continued)				
Extruded, as rolled	3300	5.27	--	--	--	(25)
	3500	3.03	--	--	--	(25)
Recrystallized[e]	3600	1.265	--	--	95	(28)
Extruded, as rolled	3700	1.80	--	--	--	(25)
		Sheet				
Sheet (0.065 inch)[a]						
Stress relieved	-390	203.2	--	--	--	(16)
	-390	208	--	--	--	(16)
Stress relieved	-165	167.8	167.8	--	29.4	(16)
	-165	162.1	160	--	24.5	(16)
Recrystallized	-165	130.9	130.9	--	0	(16)
	-165	133.6	133.6	--	[illegible]	(16)
	-140	119.2	119.2	--	0	(16)
Stress relieved	-105	147.6	135.2	--	35.5	(16)
	-105	147.8	134.5	24	35	(16)
Recrystallized	-105	111.9	111.9	--	0	(16)
	-105	111.2	111.2	--	9.2	(16)
Stress relieved	390	109.2	97.8	--	43.4	(16)
	390	105.9	93.8	--	43.9	(16)
Recrystallized	390	61	61	--	69.5	(16)
	390	58	58	--	71.9	(16)
	570	55.3	40.6	--	69.5	(16)
Sheet (1/16 inch)[f]						
As rolled	1800	66 (L)	--	6 (L)	--	(21)
	1800	74.8 (T)	44.5 (T)	[illegible] (T)	--	(21)
Stress relieved	1800	63.4 (L)	--	6 (L)	--	(21)
	1800	74.8 (T)	--	1 (T)	--	(21)
Recrystallized	1800	34.4 (L)	19.6 (L)	20 (L)	--	(21)
	1800	39.2 (T)	14.6 (T)	16 (T)	--	(21)
Stress relieved	2400	19.9 (L)	8.8 (L)	30 (L)	--	(21)
	2400	20.7 (L)	10.8 (L)	11 (L)	--	(21)
	2400	21.1 (T)	9.9 (T)	28.5 (T)	--	(21)
	2400	18.2 (T)	9.7 (T)	5 (T)	--	(21)
Recrystallized	2400	17.6 (L)	9.4 (L)	30 (L)	--	(21)
	2400	15.3 (L)	5.9 (L)	27.5 (L)	--	(21)
	2400	16.7 (T)	7.3 (T)	30 (T)	--	(21)
	2400	16.9 (T)	11.1 (T)	36 (T)	--	(21)

TABLE A-56. (Continued)

Condition	Temperature F	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation, per cent	Reduction in Area, per cent	Reference
		Sheet (Continued)				
Sheet						
0.060 inch	2400	39.9	33.5	5	--	(29)
0.040 inch	2600	18.9	11.5	12	--	(29)
0.060 inch	2600	16.2	11.4	10	--	(29)
0.040 inch	2800	15	8.4	22	--	(29)
0.060 inch	2800	12.4	8.7	10	--	(29)
0.040 inch	3000	9.8	5.7	30	--	(29)
0.060 inch	3000	10.8	6.7	20	--	(29)

(a) 0.46% Ti and 0.012% C.
(b) 0.1 per cent offset.
(c) 0.46% Ti and 0.021% C.
(d) 0.46% Ti and 0.023% C.
(e) 0.47% Ti and 0.026% C.
(f) 0.046 to 0.047% C.

TABLE A-57. EFFECT OF TEMPERATURE ON THE MODULUS OF ELASTICITY OF ARC-CAST Mo-0.5Ti BAR[a]

Reference 32[b]		Reference 24[c]		
Temperature, F	Modulus of Elasticity, 10^6 psi	Temperature, F	Strain Rate, in./in./min	Modulus of Elasticity, 10^6 psi
RT	37.1	RT	0.002	49.1
400	36.5		0.2	48.9
600	38.5	1200	0.002	35.5
800	33.5		0.2	17.0
1000	33.7	2100	0.002	16.3
1200	32.2		0.2	23.6
1400	28.5	2600	0.002	18.7
1600	29.9		0.2	39.2
1800	27.8	3000	0.002	5.5
2000	25.5			
2200	18.9			
2400	8.55			

(a) Data from compressive tests.
(b) From 3/4-inch hot-cold-rolled stress-relieved bar. Test rate 0.05 inch per minute in argon.
(c) 3/8-inch diameter bar recrystallized 35 minutes at 2900 F, ASTM 6.

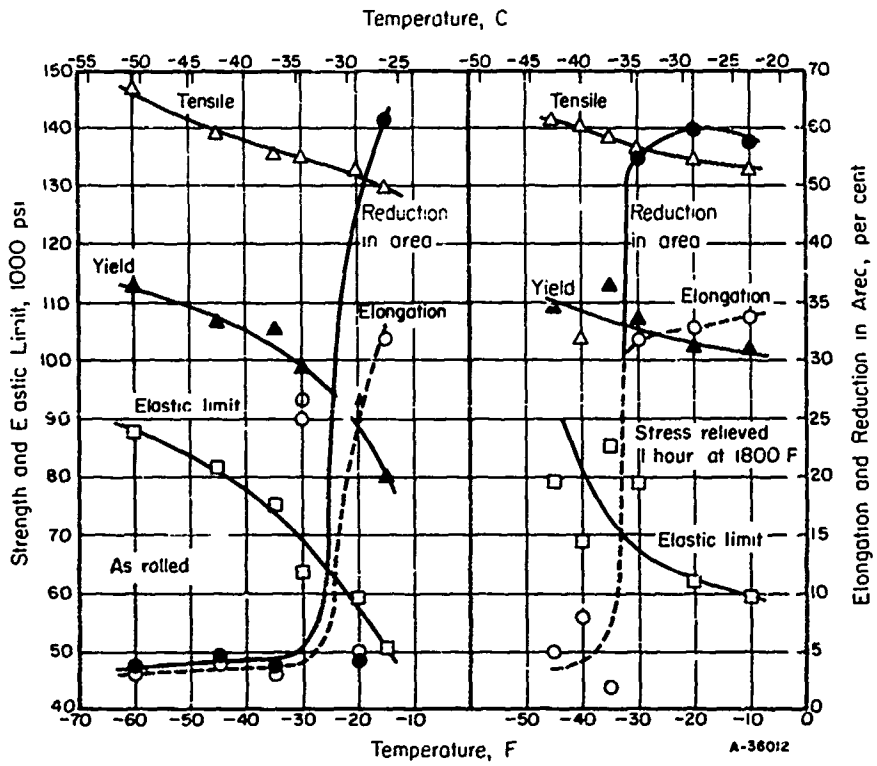


FIGURE A-88. LOW-TEMPERATURE TENSILE PROPERTIES OF AS-ROLLED AND STRESS-RELIEVED Mo-0.5Ti BAR (5/8-INCH DIAMETER)[17]

Analyses 0.46% Ti and 0.021% C.

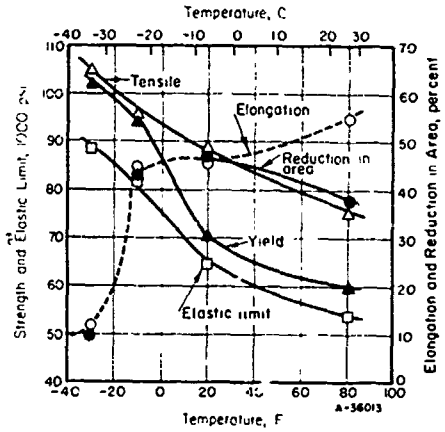


FIGURE A-89. LOW-TEMPERATURE TENSILE PROPERTIES OF RECRYSTALLIZED Mo-0.5Ti BAR (5/8-INCH DIAMETER)[17]

Recrystallized 1 hour at 2450 F.

Analyses 0.45% Ti and 0.024% C.

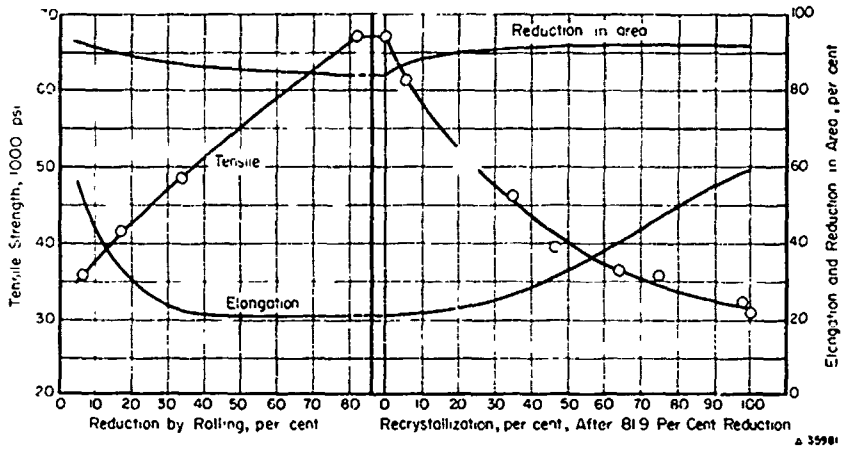


FIGURE A-90. TENSILE PROPERTIES OF Mo-0.5Ti BAR (3/4 INCH SQUARE) AT 1800 F

Rolled at 1800 F.

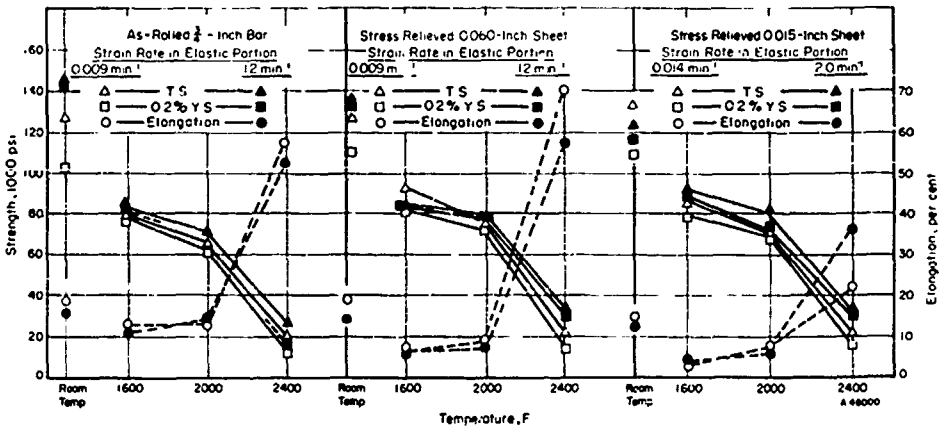


FIGURE A-91. EFFECT OF STRAIN RATE ON THE ELEVATED-TEMPERATURE TENSILE PROPERTIES OF ARC-CAST Mo-0.5Ti BAR AND SHEET(30)

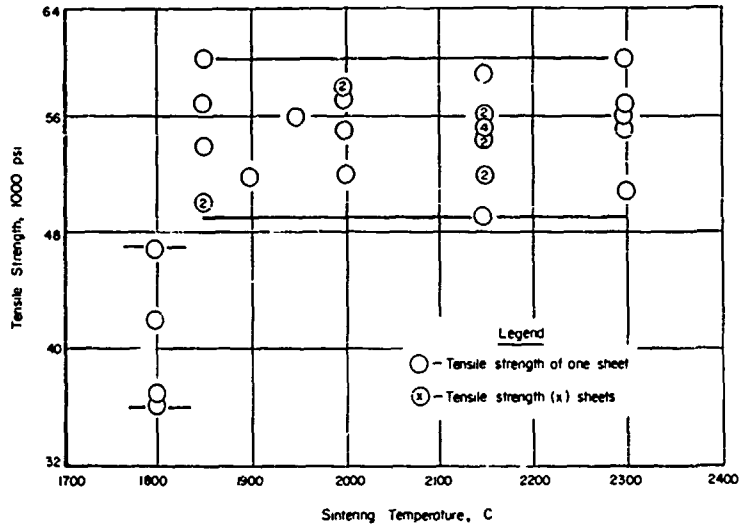


FIGURE A-92. EFFECT OF SINTERING TEMPERATURE ON THE TENSILE STRENGTH OF SYLVANIA POWDER-METALLURGY Mo-0.5Ti SHEET (0.040 INCH) AT 2190 F[31]

0.015 to 0.066% carbon.

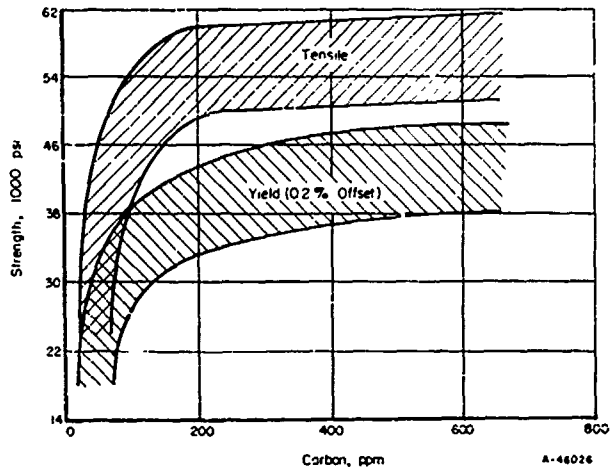


FIGURE A-93. EFFECT OF CARBON CONTENT ON THE 1200 C STRENGTH PROPERTIES OF SYLVANIA POWDER-METALLURGY Mo-0.5Ti SHEET (0.040 INCH) ROLLED FROM BILLETS SINTERED AT 1850 TO 2300 C[31]

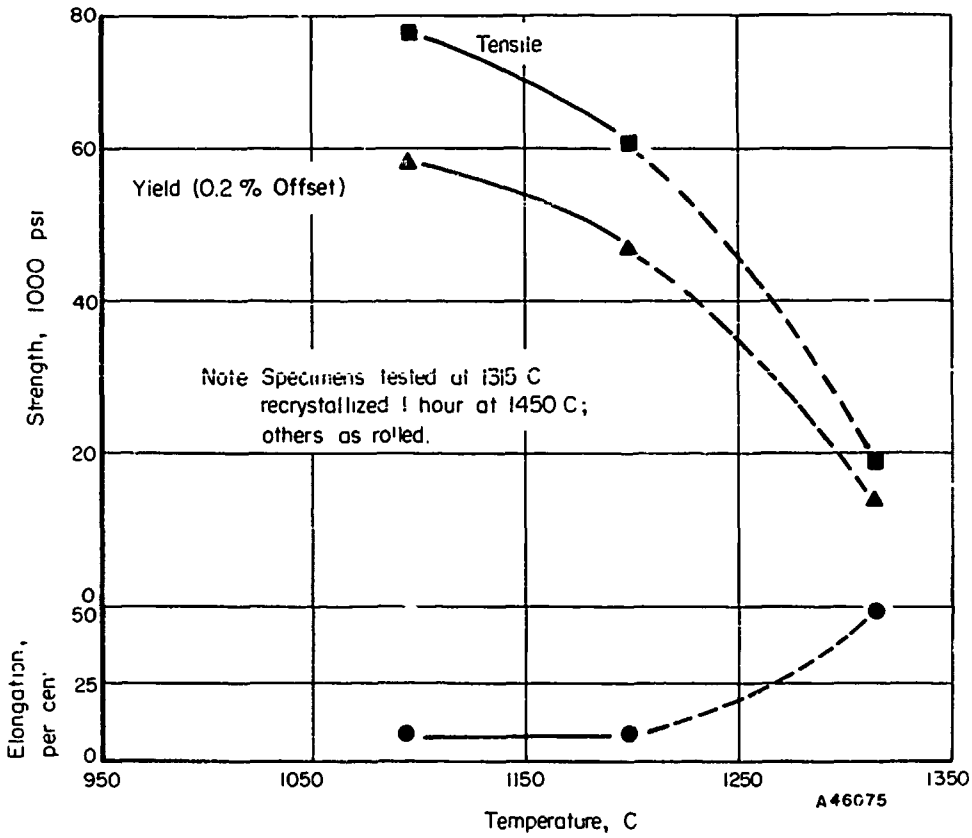


FIGURE A-94. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF SYLVANIA POWDER-METALLURGY Mo-0.5Ti SHEET (0.040 INCH)[31]

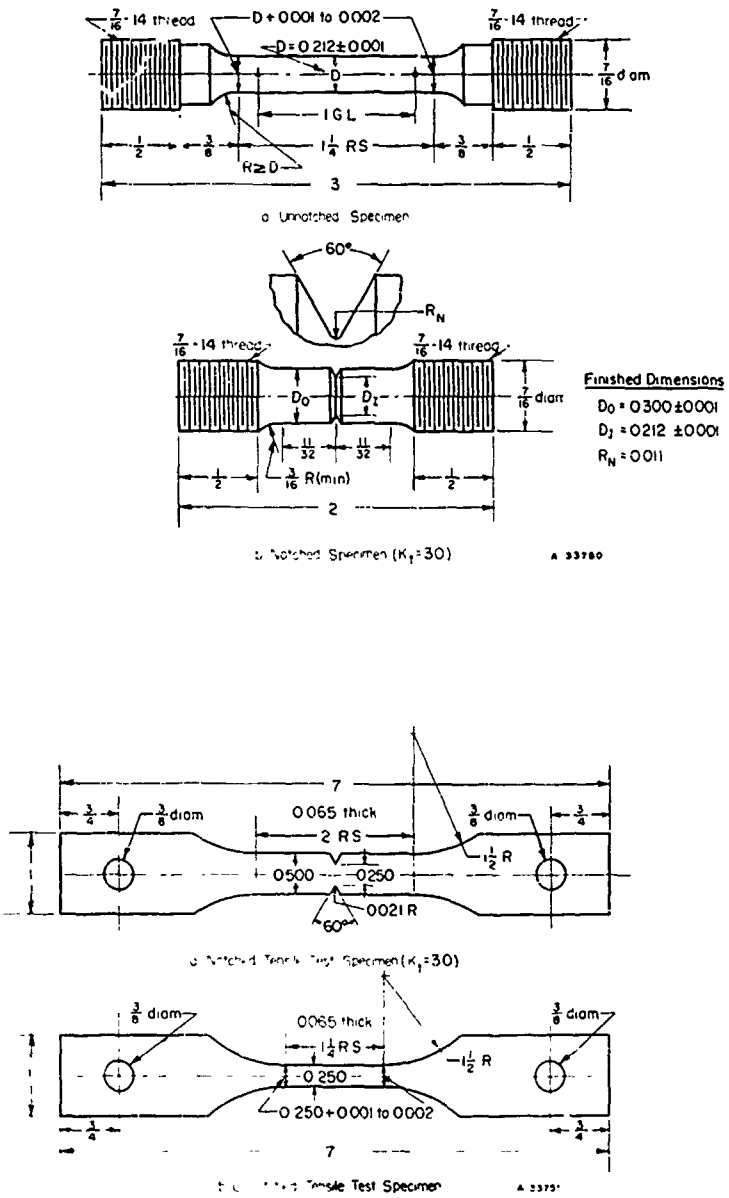


FIGURE A-95. UNNOTCHED AND NOTCHED BAR AND SHEET TENSILE TEST SPECIMENS USED TO OBTAIN DATA SHOWN IN FIGURES A-96 THROUGH A-99

All dimensions are in inches.

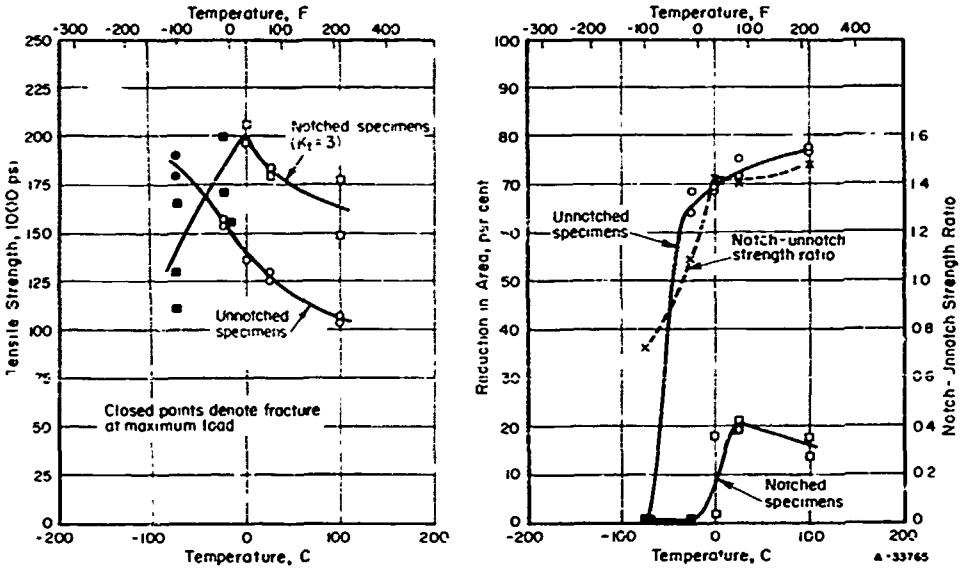


FIGURE A-96. TENSILE PROPERTIES FOR WROUGHT, STRESS-RELIEVED ARC-MELTED Mo-0.5Ti BAR (1/4 HR AT 1200 C; HARDNESS 272 VHN)[16]

	Unnotched	Notched
Crosshead Speed, inch per minute	0.02	0.005

Impurity	Weight Per Cent
C	0.012
O	<0.0020
N	0.001
H	0.0006
Ti	0.5
Ta	<0.2
W	<0.1
Others	<0.06

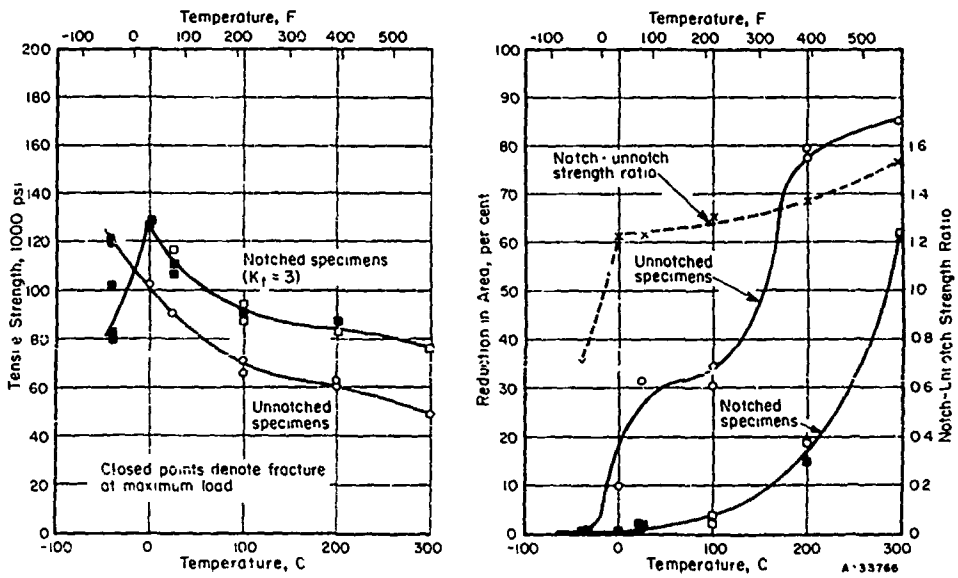


FIGURE A-97 TENSILE PROPERTIES FOR RECRYSTALLIZED ARC-MELTED Mo-0.5Ti BAR (1/4 HR AT 1400 C; HARDNESS 201 VHN; ASTM 8.1)[16]

	Unnotched	Notched
Crosshead Speed, inch per minute	0.02	0.005

Impurity	Weight Per Cent
C	0.012
O	<0.0020
N	0.001
H	0.0006
Ti	0.5
Ta	<0.2
W	<0.1
Others	<0.06

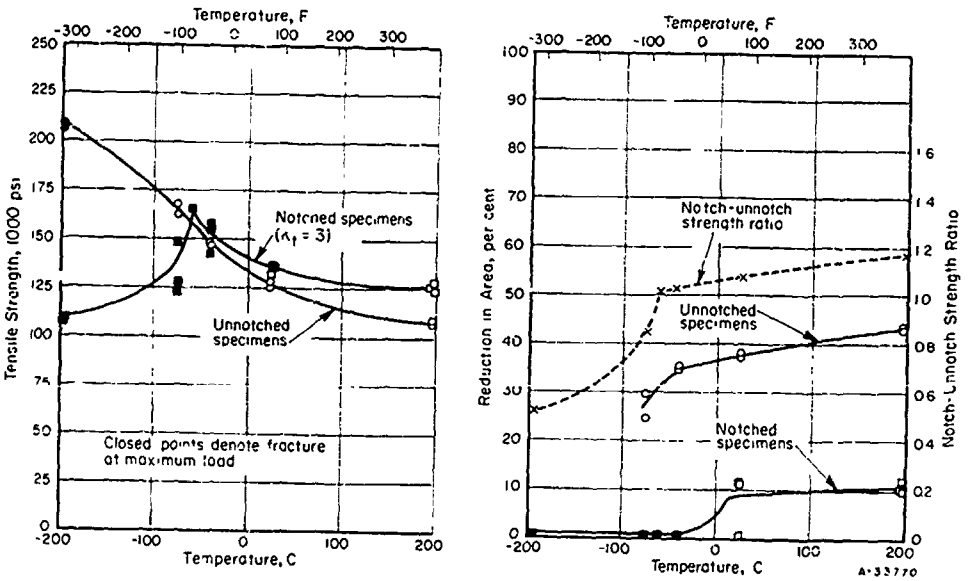


FIGURE A-98. TENSILE PROPERTIES FOR WROUGHT, STRESS-RELIEVED ARC-MELTED Mo-0.5Ti SHEET (AS RECEIVED, HARDNESS 267 VHN)[12]

	Unnotched	Notched
Crosshead Speed, inch per minute	0.02	0.005

Impurity	Weight Per Cent
C	0.020
O	0.0042
N	0.001
H	0.0005
Ti	0.5
Ta	<0.2
W	<0.1
Others	0.05

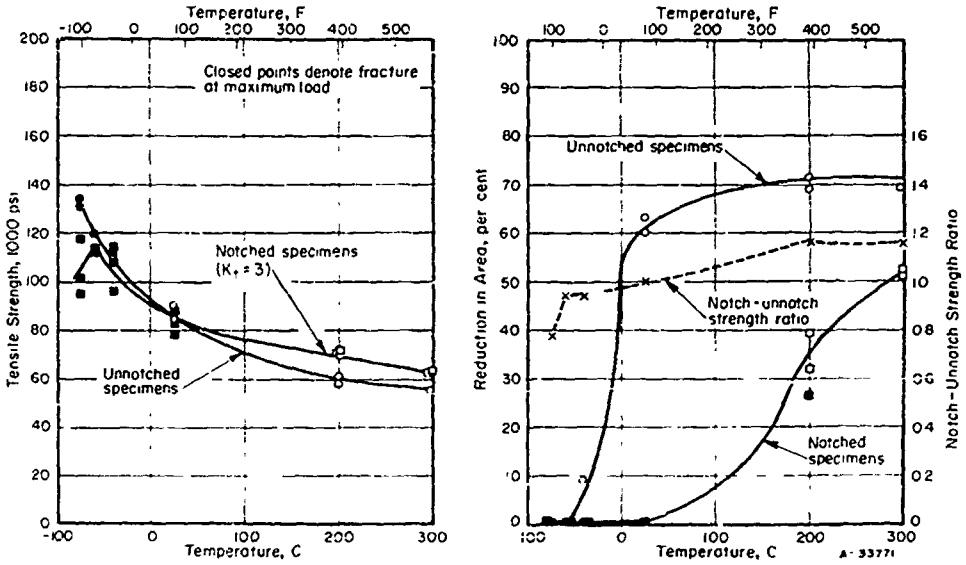


FIGURE A-99. TENSILE PROPERTIES FOR RECRYSTALLIZED ARC-MELTED Mo-0.5Ti SHEET (3/4 HR AT 1410 C; HARDNESS 183 VHN, ASTM 8.4)[12]

	Unnotched	Notched
Crosshead Speed, inch per minute	0.02	0.005

Impurity	Weight Per Cent
C	0.020
O	0.0042
N	0.001
H	0.0005
Ti	0.5
Ta	0.2
W	0.1
Others	<0.05

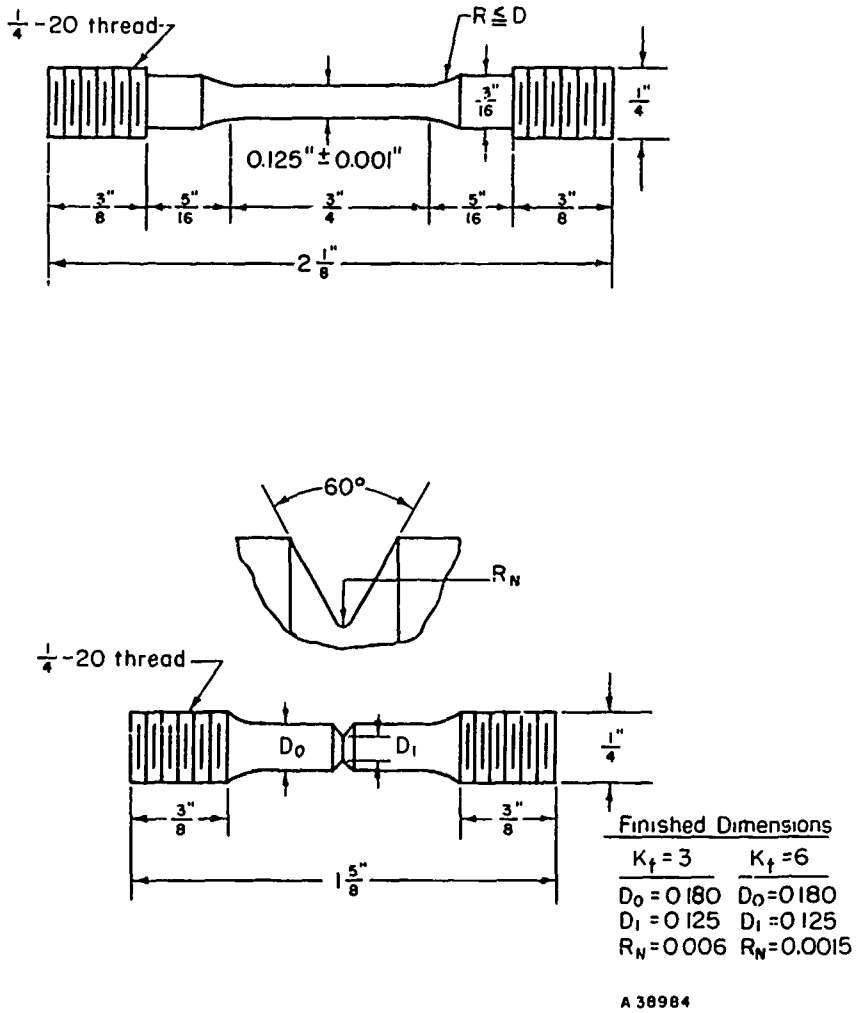


FIGURE A-100. UNNOTCHED AND NOTCHED BAR TENSILE TEST SPECIMENS USED TO OBTAIN DATA SHOWN IN FIGURES A-101 THROUGH A-103

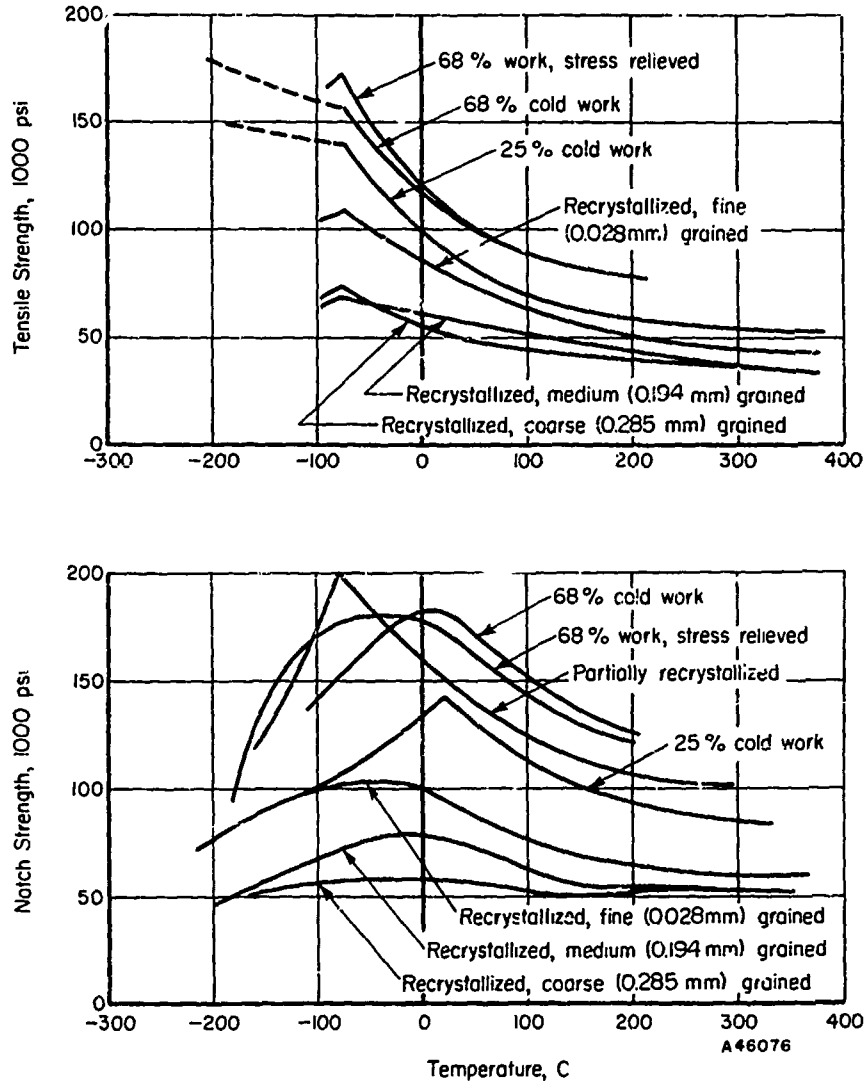


FIGURE A-101. EFFECT OF STRUCTURE ON THE UNNOTCHED AND NOTCHED TENSILE STRENGTH OF ARC-CAST Mo-0.5Ti BAR[33]

	Unnotched	Notched	Impurity	PPM
Crosshead Speed, inch per minute	0.02	0.005	C	260-290
			O	1-78
			N	<10-40
			H	<1

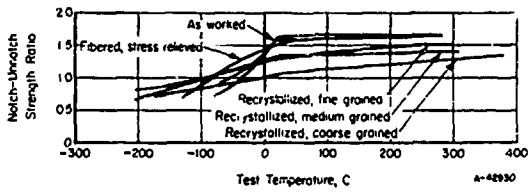
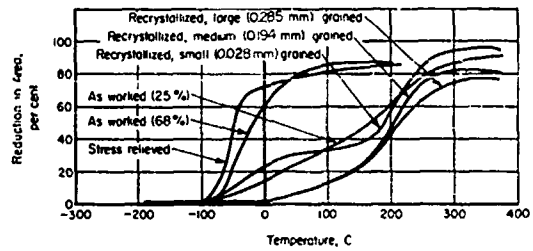


FIGURE A-102. EFFECT OF STRUCTURE ON NOTCH-UNNOTCH STRENGTH RATIO OF ARC-CAST Mo-0.5Ti BAR(33)

	Unnotched	Notched	Impurity	PPM
Crosshead Speed, inch per minute	0.02	0.005	C	260-290
			O	1-78
			N	<10-40
			H	<1



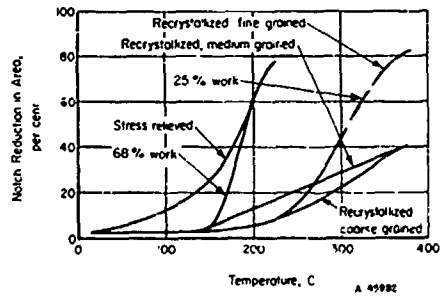


FIGURE A-103. EFFECT OF STRUCTURE ON THE UNNOTCHED AND NOTCHED REDUCTION IN AREA OF ARC-CAST Mo-0.5Ti BAR(33)

	Unnotched	Notched	Impurity	PPM
Crosshead Speed, inch per minute	0.02	0.005	C	260-290
			O	1-78
			N	<10-40
			H	<1

TABLE A-58. STRESS-RUPTURE DATA FOR STRESS-RELIEVED AND RECRYSTALLIZED Mo-0.5Ti SHEET (1/16 INCH) AT 1800 F[34]

Carbon Content, weight per cent	Condition	Stress, 1000 psi, to Produce Rupture		
		1 Hour	10 Hours	100 Hours
0.046	Stress relieved 1 hour 2000 F	67.5	59.5	52.0
	Recrystallized 1 hour 2400 F	32.5	30.0	27.5
0.047	Stress relieved 1 hour 2100 F	<62.0	--	--
	Recrystallized 1 hour 2500 F	--	34.5	29.5

TABLE A-59. EFFECT OF PRIOR FABRICATION HISTORY ON THE CREEP AND STRESS-RUPTURE PROPERTIES OF Mo-0.5Ti AT 1800 F[15]

Condition	Condition Prior to Forging	Forging Temperature, F	Stress, 1000 psi	Creep Rate, per cent/hour	Rupture Time, hours	Elongation, per cent	Reduction in Area, per cent
Varying strain hardening along specimen gage length, rolled at 2250 F, heat treated, forged	As rolled	1800	56.0	0.18	13.5	9.3	62.8
		1800	51.0	--	1.5[c]	0.7	--
		2100	58.0	--	6.9	11.5	82.2
		2100	51.0	0.056	45.3	10.5	77.4
		2400	38.0	--	8.8	10.4	89.4
		2400	32.5	0.025	234.3[c]	0.4	--
	50% recrystallized	1800	39.0	0.26	4.2	10.2	86.6
		1800	34.0	0.006	284.9	8.4	75.5
		2100	38.5	0.025	47.4	10.7	90.2
		2100	34.0	0.0038	81.0	9.9	83.3
		2400	36.0	0.028	37.1	8.1	74.4
		2400	34.5	0.05	17.7	8.9	82.7
	100% recrystallized	1800	35.0	0.01	115.4[c]	2.2	--
		1800	31.5	0.0001	233.7[a]	0.74	--
		2100	33.0	0.019	36.2	8.0	82.1
		2100	31.5	0.0013	281.2[a]	0.97	--
		2400	39.0	0.30	2.4	9.5	81.2
		2400	36.0	0.00012	209.3[a]	0.40	--
Varying strain hardening along specimen gage length, rolled at 2400 F, heat treated, forged	As rolled	1800	55.0	0.12	21.0	11.1	80.2
		1800	50.0	0.06	41.8	9.6	72.9
		2100	55.0	0.25	9.9	10.7	64.1
		2100	50.0	0.13	75.2	10.6	74.6
		2400	37.0	0.35	5.6	9.5	89.3
		2400	33.0	0.045	27.3	9.6	90.4
	50% recrystallized	1800	33.0	0.13	9.3	9.5	85.7
		1800	29.0	0.035	71.1	10.4	90.9
		2100	35.5	0.10	1.6	9.6	91.8
		2100	30.5	0.00003	190.5[a]	0.27	--
		2400	38.0	0.01	23.9	9.3	86.0
		2400	35.0	0.021	20.1	9.3	85.7
Varying strain hardening along specimen gage length, rolled at 2400 F, heat treated, forged	100% recrystallized	1800	32.0	0.008	53.4	9.3	91.9
		1800	29.0	0.003	138.4[a]	2.1	--
		2100	34.5	0.0035	125.1[a]	0.86	--
		2100	32.0	0.007	153.4	8.6	90.0
		2400	33.0	0.56	5.9	10.3	92.9
		2400	29.0	0.001	185.8[a]	0.81	--

(a) Test discontinued.
(b) Estimated.
(c) Test discontinued because specimen holder failed.
(d) Value attained on loading.

TABLE A-60. CREEP AND STRESS-RUPTURE PROPERTIES OF STRESS-RELIEVED Mo-0.5Ti AT 1000 TO 2000 F[35]

Temperature, F	Stress, 1000 psi	Time, hours, to Reach Indicated Per Cent of Deformation					Minimum Creep Rate, per cent/hour	Rupture Time, hours	Elongation, per cent	Reduction in Area, per cent
		0.2	0.5	1.0	2	5				
1000	85.5	--	--	--	--	--	-	(a)	12.0	84.5
	75.0	(a)	--	--	--	--	Nil	200.4[b]	0.47	--
1200	82.5	--	--	--	--	--	--	(a)	12.0	82.1
	78.5	(a)	0.1	62	--	--	0.0016	255.1[b]	1.33	--
1400	76.0	--	--	--	--	--	--	(a)	12.0	73.1
	70.0	(a)	0.3	19	108	242, est.	0.011	254.7	15.2	72.1
1600	85.0	--	--	0.06	0.3	--	1.0	0.5	14.9	86.8
	75.0	--	6.2	1.7	5	15	0.22	18.2	17.4	88.3
	70.0	1	4	14	42	--	0.031	138.0	17.1	72.7
	65.0	7	18	38	70	145	0.03	171.0	17.5	77.5
1800	70.0	(a)	(a)	0.13	0.4	0.9, est.	3.2	1.0	16.5	83.2
	60.0	0.2	1.6	4.0	8.7	20, est.	0.21	27.5	18.5	88.0
	55.0	2.7	7.7	18	33	80	0.037	94.6	18.0	83.6
	50.0	5.5	16	34	125	210, est.	0.012	227.9	16.3	61.8
	48.0	--	--	--	--	--	0.003, est.	550.0	12.8	51.7
	45.0	7.2	27	260	595	--	0.0014	910.0[b]	3.22	--
2000	70.0	--	--	--	--	--	--	0.2	12.1	79.8
	50.0	--	0.1	0.75	2.5	--	0.52	6.7	19.2	87.6
	30.0	--	3.5	37	192	--	0.0012	257.2	10.3	39.6
	27.0	--	9.0	55	197	--	0.009	501.2	11.5	6.8
	25.0	--	15	75	235	--	0.0062	335.8[b]	2.3	--
	20.0	--	25	163	--	--	0.004	261.5[b]	1.4	--

(a) Value attained on loading.
(b) Indicates test was discontinued at this time.

TABLE A-61. CREEP AND STRESS-RUPTURE PROPERTIES OF RECRYSTALLIZED Mo-0.5Ti AT 1000 TO 2400 F[35]

Temperature, F	Stress, 1000 psi	Time, hours, to Reach Indicated Per Cent of Deformation						Minimum Creep Rate, per cent/hour	Rupture Time, hours	Elongation, per cent	Reduction in Area, per cent
		3	5	8	10	12	15				
1000	38.0	--	--	(a)	--	--	--	Nil	256.1[b]	8.54	--
1200	38.0	--	--	(a)	--	--	--	0.0004	216.4[b]	8.62	--
	36.0	--	--	--	--	--	--	0.0005	232.4[b]	36.8	--
1400	35.0	--	--	100	202	268	378	0.017	402.5[b]	15.9	--
1600	40.0	--	(a)	0.3	0.5	0.8	1.0	--	1.7	44.8	90.4
	35.0	(a)	1.5	11	21	32	48	0.19	74.9	32.8	86.4
	34.0	(a)	8.0	72	128	178	210	0.037	223.0	25.0	61.1
	33.5	(a)	8.0	54	116	178	310	0.027	379.4[b]	15.3	--
1800	35.0	--	--	(a)	0.04	0.08	0.10	--	0.35	50.5	92.3
	31.0	(a)	0.29	0.4	0.7	1.1	1.7	5.8	3.9	45.6	89.7
	29.0	0.18	1.0	5.0	11	17	27	0.32	82.3	63.2	89.4
	27.5	0.7	4.7	10	13	22	47	0.014	328.7[b]	22.4	--
2000	30.0	--	(a)	0.06	0.1	0.11	0.2	--	0.[illegible]	48.3	89.7
	25.0	(a)	--	0.1	0.16	0.2	0.5	6.0	4.4	51.7	86.7
	20.0	2.3	13	37	55	75	115	0.11	221.1	32.8	38.2
	18.0	43	125	210	249	285. est.	--	0.023	280.0[b]	12.6	--
2400	5.0	--	--	--	--	--	--	0.013	258.9	4.2	5.8
	3.0	--	--	--	--	--	--	0.0023	834.4[b]	1.90	--
	2.0	--	--	--	--	--	--	0.0003	361.0[b]	0.188	--
	1.0	--	--	--	--	--	--	0.00011	799.3[b]	0.077	--

(a) Value attained on loading.
(b) Indicates test was discontinued at this time.

TABLE A-62. SOME SELECTED CREEP AND STRESS-RUPTURE PROPERTIES OF Mo-0.5Ti AT ELEVATED TEMPERATURES

Composition and Condition	Temperature, F	Stress, 1000 psi	Creep Rate, per cent/hour	Rupture Time, hours	Elongation, per cent	Reduction in Area, per cent	Reference
0.45% Ti, stress relieved	1600	85.0	4.0	0.5	14.9	86.8	(17)
		75.0	0.22	18.2	17.4	88.3	(17)
		65.0	0.03	171.0	17.5	77.5	(17)
	1800	70.0	3.2	1.0	16.5	83.2	(17)
		60.0	0.21	27.5	18.5	88.0	(17)
		50.0	0.0212	227.9	16.3	61.8	(17)
	2000	70.0	--	0.2	12.1	79.8	(17)
		50.0	0.52	6.7	19.2	87.6	(17)
		20.0	0.004	261.6[a]	2.4	--	(17)
0.45% Ti, recrystallized	1600	40.0	--	1.7	44.8	90.4	(17)
		35.0	0.19	74.9	32.8	86.4	(17)
		33.5	0.027	379.4[a]	15.3	--	(17)
	1800	35.0	--	0.35	50.5	92.3	(17)
		31.0	5.8	3.9	45.6	89.7	(17)
		27.5	0.013	328.7[a]	22.4	--	(17)
	2000	30.0	--	0.3	48.3	79.7	(17)
		25.0	6.0	4.4	51.7	86.7	(17)
		18.0	0.023	280.0[a]	12.6	--	(17)
0.46% Ti, stress relieved	1600	70.0	0.031	138.0	17.1	72.7	(17)
	1800	55.0	0.037	94.0	18.0	83.6	(17)
		48.0	0.003	550.0	12.8	51.7	(17)
		45.0	0.0014	335.8[a]	3.2	--	(17)
	2000	30.0	0.0042	257.2	10.3	39.6	(17)
		27.0	0.009	501.2	11.5	6.8	(17)
		25.0	0.0062	335.8[a]	--	--	(17)
0.46% Ti, recrystallized	1600	34.0	0.037	223.0	25.0	61.1	(17)
	1800	29.0	0.32	82.3	63.2	83.4	(17)
	2000	20.0	0.11	221.1	32.8	88.2	(17)
0.46% Ti and 0.021% C, as rolled	2400	15.0	3.80	3.2	37.2	83.8	(19)
		10.0	0.005	95.4	15.6	90.6	(19)
0.5% Ti, stress relieved	1000	85.5	--	(b)	12.0	84.5	(36)
		75.0	Nil	260.4[c]	0.47	--	(36)
	1200	82.5	--	(b)	12.0	82.1	(36)
		78.5	0.0016	255.4[c]	1.33	--	(36)
	1400	76.0	--	(b)	12.0	73.1	(36)
		70.0	0.011	254.7	15.2	72.1	(36)

TABLE A-62 (Continued)

Composition and Condition	Temperature, F	Stress, 1000 psi	Creep Rate, per cent/hr	Rupture Time, hours	Elongation, per cent	Reduction in Area, per cent	Reference
0.5% Ti, stress relieved (Continued)	1600	85.0	[illegible]	0.5	14.9	86.8	(36)
		75.0	.22	18.2	17.4	88.3	(36)
		70.0	0.031	138.0	17.1	72.7	(36)
		65.0	0.03	171.0	17.5	77.5	(36)
	1800	70.0	3.2	1.0	16.5	83.2	(36)
		60.0	0.21	27.5	18.5	88.0	(36)
		55.0	0.037	94.6	18.0	83.6	(36)
		50.0	0.012	227.9	16.3	61.8	(36)
		48.0	0.00[illegible] cent.	550.0	12.8	51.7	(36)
		45.0	0.0014	910.0(c)	3.22	--	(36)
	2000	70.0	--	0.2	12.1	79.8	(36)
		50.0	0.52	6.7	19.2	87.6	(36)
		30.0	0.0042	259.2	10.3	39.6	(36)
		27.0	0.009	501.2	11.5	6.8	(36)
		25.0	0.0062	225.8(c)	2.3	--	(36)
		20.0	0.004	261.6(c)	1.4	--	(36)
0.5% Ti, recrystallized	1000	38.0	Nil	256.1(c)	8.54	--	(36)
	1200	38.0	0.0004	216.4(c)	8.62	--	(36)
		36.0	0.0005	232.4(c)	36.8	--	(36)
	1400	35.0	0.017	402.5(c)	15.9	--	(36)
	1600	40.0	--	1.7	44.8	96.4	(36)
		35.0	0.19	74.9	32.8	86.4	(36)
		34.0	0.037	223.0	25.0	61.1	(36)
		33.5	0.027	379.4(c)	15.3	--	(36)
	1800	35.0	--	0.35	50.5	92.3	(36)
		31.0	5.8	3.9	45.6	89.7	(36)
		29.0	0.32	82.3	63.2	89.4	(36)
		27.5	0.014	328.7(c)	22.4	--	(36)
	2000	30.0	--	0.3	48.3	89.7	(36)
		25.0	6.6	4.4	51.7	86.7	(36)
		20.0	0.11	221.1	32.8	88.2	(36)
		18.0	0.023	280.6(c)	12.6	--	(36)
	2400	5.0	0.013	258.9	4.2	5.8	(36)
		3.0	0.0022	834.4(c)	1.90	--	(36)
		2.0	0.0003	361.0(c)	0.188	--	(36)
		1.0	0.00011	700.3(c)	0.077	--	(36)

(a) Test discontinued.
(b) Value attained on loading.
(c) Estimated.

TABLE A-63. CREEP AND STRESS-RUPTURE PROPERTIES OF RECRYSTALLIZED ARC-CAST Mo-0.5Ti BAR (3/8-INCH DIAMETER) IN ARGON[a][24]

Temperature, F	Stress 1000 psi	Time, min, to Produce Indicated Amount of Deformation 1%	2%	5%	Rupture	Elongation, per cent
2100	16.0	35.2	112.0	--	--	--
	19.0	[illegible]	3.8	200.0	--	--
	19.5		123.0	--	--	--
	20.0		2.2	6.5	104.0	25
2600	8.5		4.75	29.5	79.0	24
	10.0	0.1	0.5	11.2	40.0	23
	12.0	0.5	1.3	4.5	11.0	23
	13.0	0.2	0.4	3.0	19.0	25
3000	2.0	38.0	77.0	244.0	390.0	--
	2.5	36.0	60.0	111.0	127.0	18
	3.0	3.0	7.5	19.5	31.2	23

(a) Recrystallized 35 minutes at 2900 F, ASTM 6.

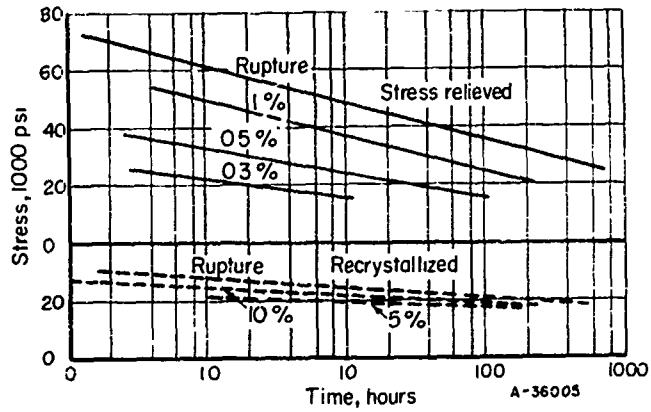


FIGURE A-104. CREEP AND STRESS-RUPTURE PROPERTIES OF STRESS-RELIEVED AND RECRYSTALLED Mo-0.5Ti AT 2000 F[37]

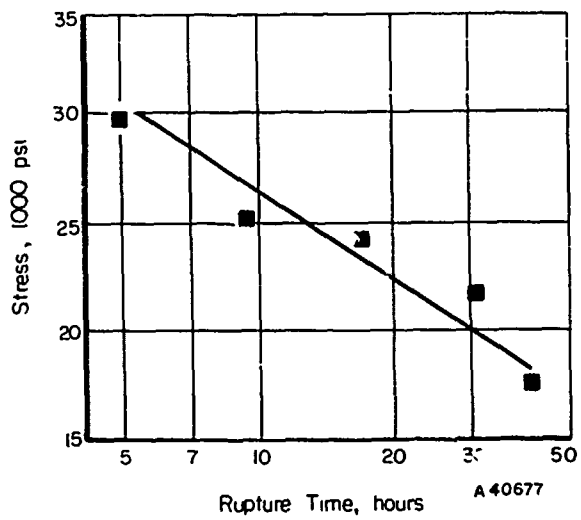
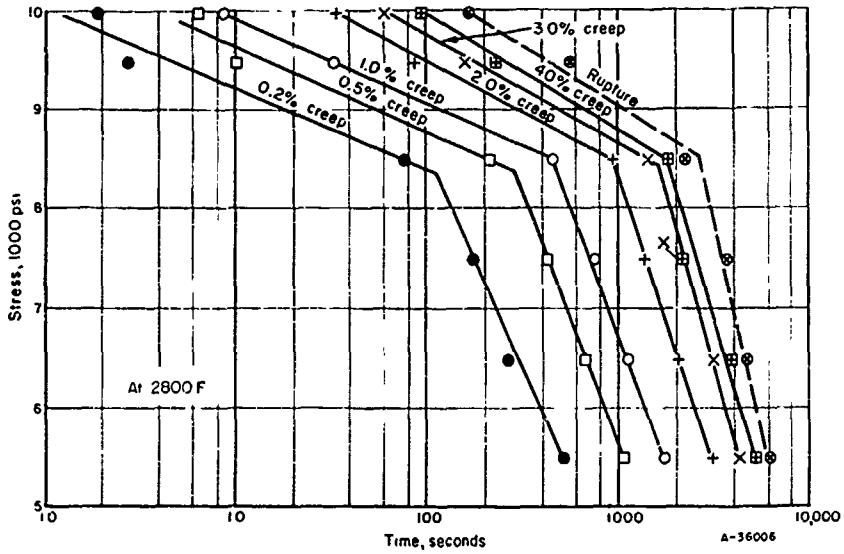


FIGURE A-105. STRESS-RUPTURE CHARACTERISTICS OF SYLVANIA POWDER-METALLURGY Mo-0.5Ti SHEET (0.040 INCH) AT 2190 F[31]



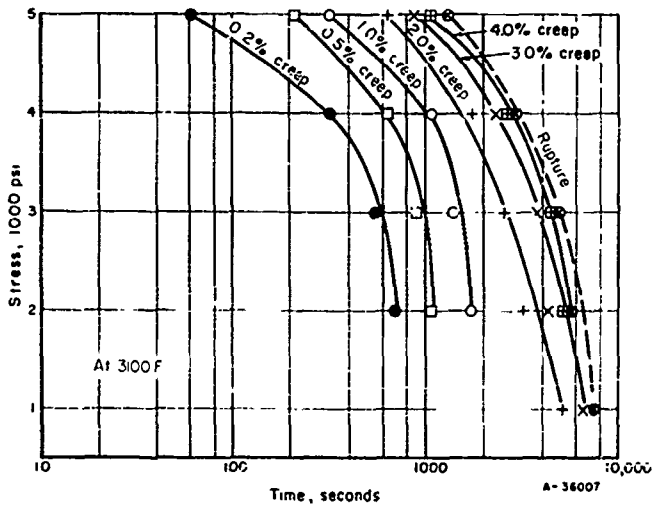


FIGURE A-106. HIGH-TEMPERATURE SHORT-TIME CREEP AND STRESS-RUPTURE PROPERTIES OF ARC-CAST Mo-0.5Ti SHEET[25]

TABLE A-64 HARDNESS SPECIFICATION FOR WROUGHT AND RECRYSTALLIZED ARC-CAST Mo-0.5Ti BARS[a][c]

Diameter, inches	Hardness, DPH[b] Minimum	Maximum
	Wrought	
Over 13/32 to 7/8	250	310
Over 7/8 to 1 1/8	240	290
Over 1-1/8 to 1-7/8	235	285
Over 1-7/8 to 2-7/8	230	280
Over 2-7/8 to 3-1/2	225	275
Over 3-1/2 to 4-1/2	220	270
	Recrystallized	
Over 13/32 to 4-1/2	--	210

(a) Hardness determined at mid-radius of bar.
(b) 10-kg load.

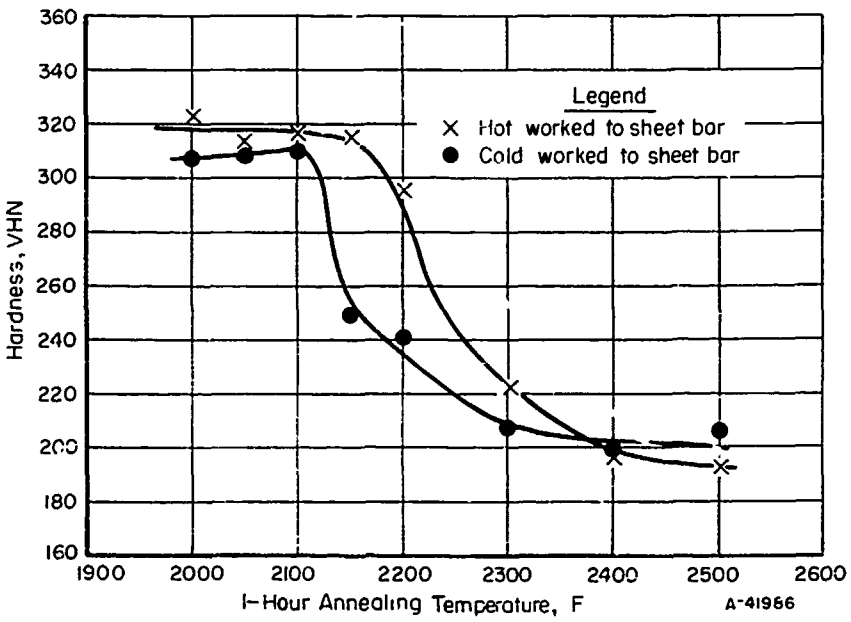


FIGURE A-107. EFFECT OF ANNEALING TEMPERATURE ON THE ROOM-TEMPERATURE HARDNESS OF Mo-0.5T.[38]

TABLE A-65. BEND-DUCTILITY REQUIREMENTS FOR ARC-CAST Mo-0.5Ti PLATE AND SHEET[a]

Direction of Bend Axis	Bend Radius Value, T	
	Maximum	Typical
Plate, up to 0.250 Inch[9]		
Parallel to rolling	3	1
Transverse to rolling	3	1
Sheet[10]		
Parallel to rolling	2	0
Transverse to rolling	2	0

(a) 3/4 by 2-inch specimens. Moderate loading rate.

TABLE A-66 BEND-TEST DATA FOR Mo-0.5Ti SHEET (1/16 INCH)[21]

Carbon Content, weight per cent	Condition	Specimen Orientation[a], degrees	Temperature, F, for Indicated Bend Angle		Bend Angle at 75 F, degrees
			10 Degrees	90 Degrees	
0.016	As rolled	90	50	188	22
	Stress relieved	90	230	260	0
	Recrystallized	90	163	322	1
0.019	As rolled	90	16	150	59
	Stress relieved	90	-76	140	75
	Recrystallized	90	6	50	131
0.046	As rolled	0	185	200	0
	Stress relieved	0	84	155	5
	Recrystallized	0	242	310	0
	As rolled	90	228	352	0
	Stress relieved	90	90	324	8
	Recrystallized	90	228	352	0
0.047	As rolled	0	155	392	0
	Stress relieved	0	280	375	0
	Recrystallized	0	234	360	0
	As rolled	90	280	>420	0
	Stress relieved	90	177	320	0
	Recrystallized	90	280	>420	0

(a) Orientation of long dimension with rolling direction.

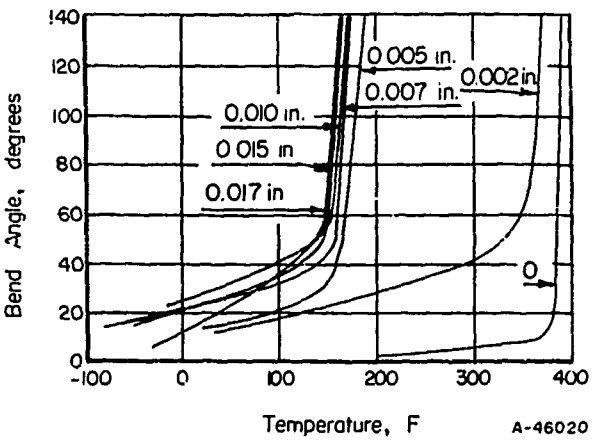


FIGURE A-108. EFFECT OF TEMPERATURE AND AMOUNT OF SURFACE REMOVED BY CHEMICAL MILLING ON THE BEND PROPERTIES OF STRESS-RELIEVED Mo-0.5Ti SHEET (0.062 INCH, INITIALLY)[34]

Stress relieved 15 minutes at 2100 F. Specimens cut parallel to rolling direction. 0.047% carbon.

TABLE A-67 EFFECT OF TEMPERATURE ON THE COMPRESSIVE YIELD STRENGTH OF ARC-CAST Mo-0.5Ti BAR (3/4-INCH DIAMETER)[a][32]

Temperature, F	Compressive Yield Strength (0.2% Offset), 1000 psi
RT	112.8
400	86.1
600	84.2
800	80.2
1000	79.6
1200	77.7
1400	73.2
1600	69.8
1800	66.2
2000	60.5
2200	19.9
2400	11.95

(a) Tested in argon at 0.05 inch per minute.

TABLE A-68 EFFECT OF STRAIN RATE AND TEMPERATURE ON THE COMPRESSIVE YIELD STRENGTH OF RECRYSTALLIZED ARC-CAST Mo-0.5Ti BAR (3/8-INCH DIAMETER) IN ARGON[a][24]

Temperature, F	Strain Rate, in./in./min	Compressive Yield Strength (0.2% Offset), 1000 psi
RT	0.002	57.6/48.2[b]
	0.2	74.9/68.2
1200	0.002	15.2
	0.2	15.0
2100	0.002	12.28
	0.2	10.47
2600	0.002	10.37
	0.2	8.76
3000	0.002	3.30
	0.2	4.84

(a) Recrystallized 35 minutes at 2900 F, ASTM 6.
(b) Upper yield strength/lower yield strength.

TABLE A-69. EFFECT OF TEMPERATURE ON THE SHEAR STRENGTH OF ARC-CAST Mo-0.5Ti SHEET[30]

Temperature, F	Shear Strength, 1000 psi	
	0.015 Inch Sheet	0.060 Inch Sheet
-100	109	61
-50	105	86
0	100	85, 88
32	91	92
75	84	87
200	67, 72	68, 73
400	70	67
600	64	66
800	63	57
1000	60	57
1200	58	52
1400	54	52
1600	49	48
1800	46	43

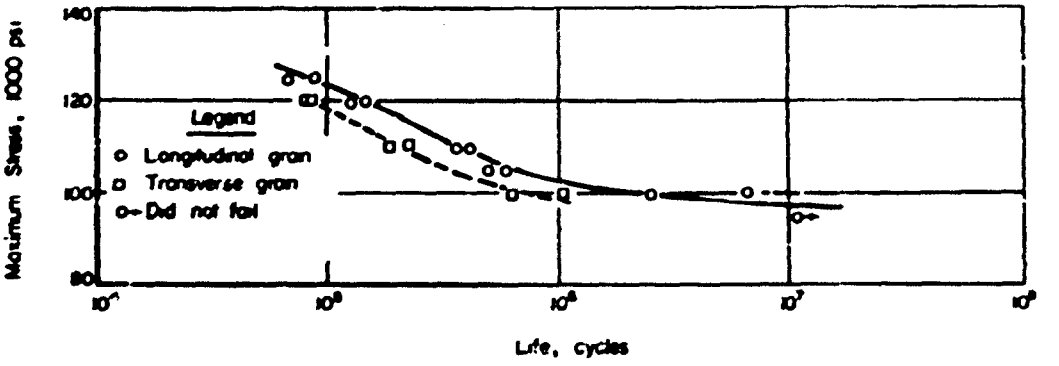


FIGURE A-109. COMPLETELY REVERSED SHEET-BENDING FATIGUE PROPERTIES OF STRESS-RELIEVED Mo-0.5 Ti SHEET (0.020 INCH) AT ROOM TEMPERATURE[40]

Analyses 0.46% Ti and 0.02% C.

4. Metallurgical Properties

a. Fabricability: initial breakdown of as-cast ingots is usually done by extrusion, practice for the production of sheet material having the best combination of properties includes: (1) roll hot-forged sheet bar at 2200 F to final mold out, (2) cold work at 1600 F up to 90 per cent, and (3) cross roll final 75 per cent from stress-relieved mold out[41]; recommended working temperature after extrusion is illustrated in Figure A-110

b. Transition temperature: for as-rolled powder-metallurgy sheet (0.040 inch)[31]

Direction	Ductile-Brittle Transition Temperature, C	
	Range	Average
Longitudinal	<-75 to -25	<-40
Transverse	-25 to 0	>-17

Tables A-70 and A-71
Figure A-111

c. Weldability: can be readily welded by most standard welding techniques; properly welded arc-cast material will exhibit better characteristics (less spatter, sounder weldments) than unalloyed molybdenum — this is thought to be associated with the gettering action of titanium, welds are room-temperature ductile[43]

d. Stress-relief temperature: 1/4 hour at 2190 F for bar (7/16-inch diameter)[16]; 1/4 to 1 hour at 2000 to 2100 F for sheet (1/16 inch)[34]

e. Recrystallization temperature: Figures A-112 through A-116

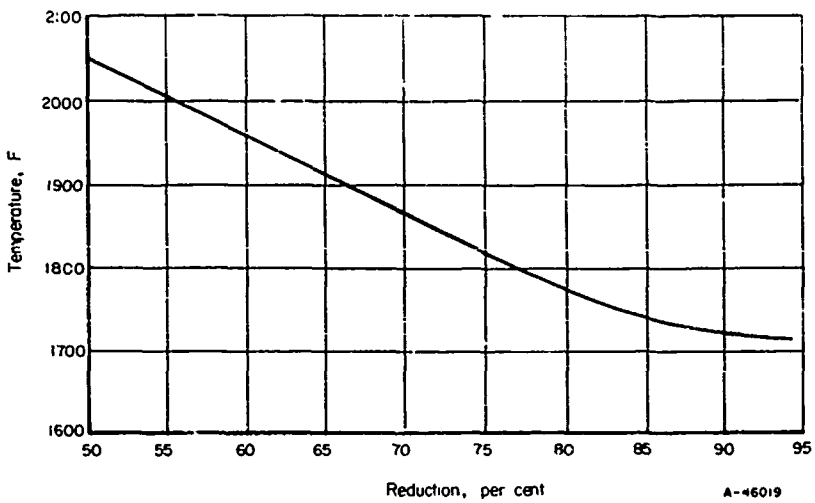


FIGURE A-110. APPROXIMATE RECOMMENDED WORKING TEMPERATURES FOR CORRESPONDING AMOUNTS OF HOT-COLD WORK FOR ARC-CAST Mo-0.5Ti[42]

TABLE A-70. EFFECT OF HEAT TREATMENT ON THE TRANSITION TEMPERATURE AND NOTCH SENSITIVITY OF Mo-0.5Ti BAR[33]

Condition	Ductility Transition Temperature, C		Difference Between Notch and Unnotched Ductility Transition Temperature, ΔC
	Unnotched	Notched (K_t = 3)	
As wrought (25%)	150	300	150
As wrought (35%)	-25	175	200
Low temp. stress relieved	-50	100	150
High temp. stress relieved	-50	175	225
Recrystallized (small grain)	50[a]	200	150
Recrystallized (medium grain)	200	325	125
Recrystallized (large grain)	200	325	125

(a) Approximate minimum of plateau.

TABLE A-71. BEND-TRANSITION TEMPERATURE REQUIREMENTS FOR ARC-CAST Mo-0.5Ti PLATE AND SHEET[a]

Direction of Bend Axis	Bend Transition Temperature, F	
	Maximum	Typical
Plate, up to 0.250 Inch[3]		
Parallel to rolling	300	70
Transverse to rolling	300	70
Sheet[10]		
Parallel to rolling	100	65
Transverse to rolling	100	65

(a) Bend-transition temperature is defined as the minimum temperature at which a specimen will bend through 105 degrees with a moderate variable loading rate over a 1T radius without failing.

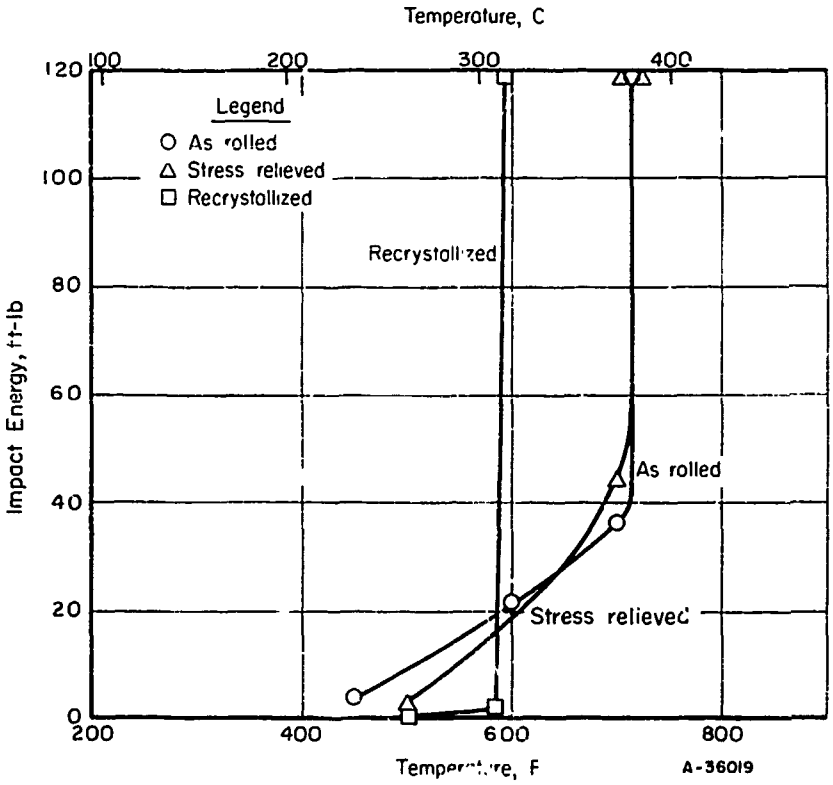
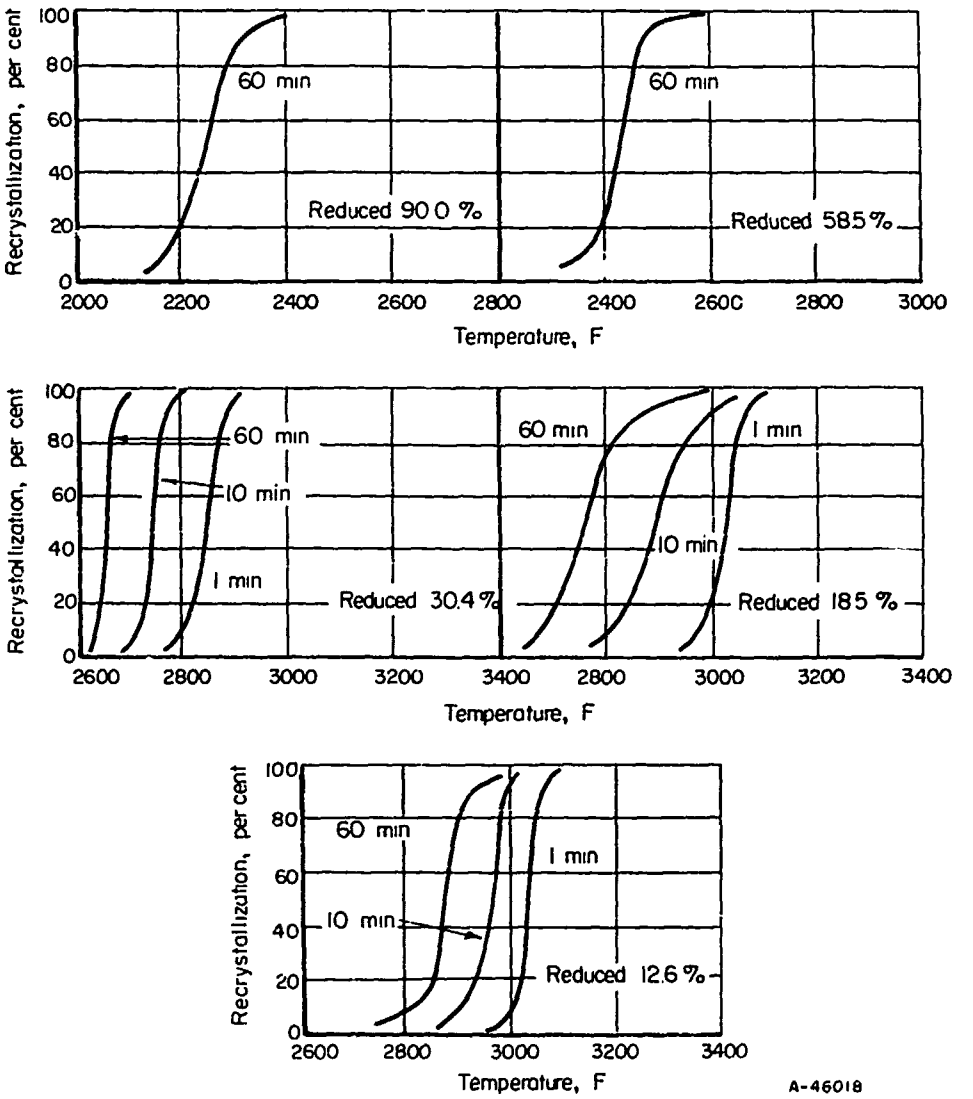


FIGURE A-111. IMPACT (V-NOTCH) TRANSITION BEHAVIOR OF Mo-0.5Ti[17]

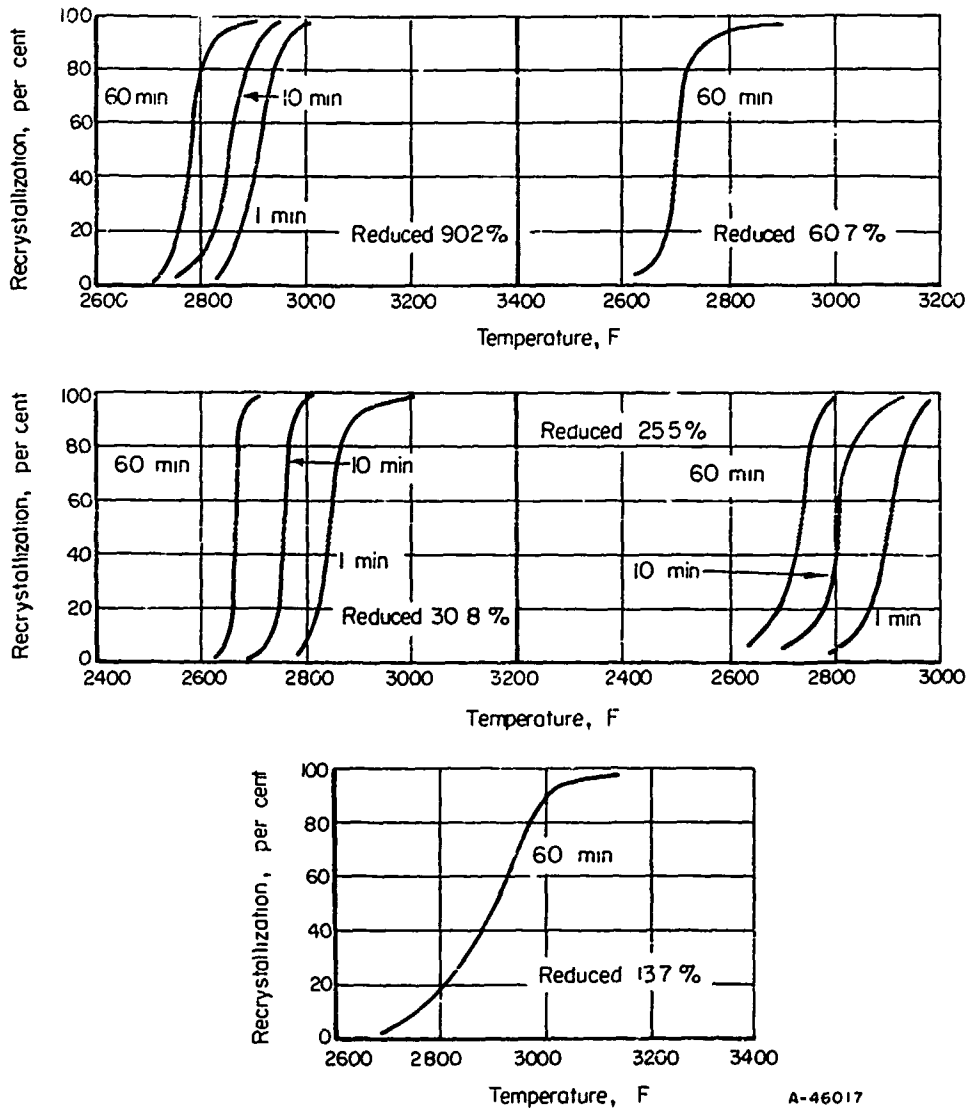
0.46% titanium.



a Rolled at 2200 F

FIGURE A-112. RECRYSTALLIZATION BEHAVIOR AS A FUNCTION OF TIME AND TEMPERATURE FOR Mo-0.5Ti BARS ROLLED TO INDICATED REDUCTIONS[44]

0.020% carbon.



b Rolled at 3000 F

FIGURE A-112. (CONTINUED)

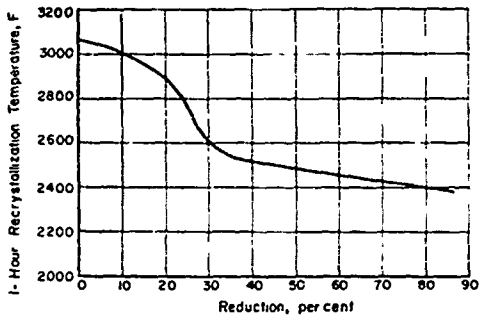


FIGURE A-113. EFFECT OF DEFORMATION ON THE MINIMUM TEMPERATURE FOR COMPLETE RECRYSTALLIZATION OF ARC-CAST MOLYBDENUM[42]

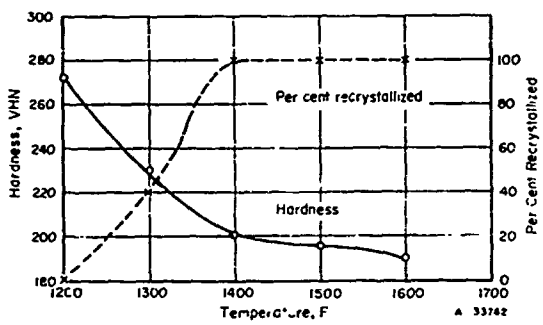


FIGURE A-114. ANNEALING CURVE FOR ARC-CAST Mo-0.5Ti BAR[16]

1/4 hour at temperature, hydrogen atmosphere, air cooled.

Arc-melted ingot swaged to 7/16-inch-diameter bar. Working temperatures generally above 600 C.

Element	Weight Per Cent
C	0.012
O	<0.0020
N	0.001
H	0.0006
Ti	0.5
Ta	<0.2
W	<0.1
Others	<0.06

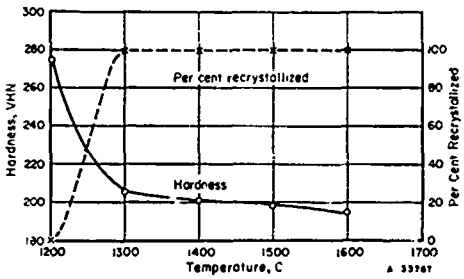


FIGURE A-115. ANNEALING CURVE FOR ARC-CAST MOLYBDENUM SHEET[16]

1/4 hour at temperature, hydrogen atmosphere, air cooled.

Arc-melted ingot rolled to 0.065-inch sheet. Working temperatures generally above 600 C.

Element	Weight Per Cent
C	0.020
O	0.0042
N	0.001
H	0.0005
Ti	0.5
Ta	<0.2
W	<0.1
Others	<0.05

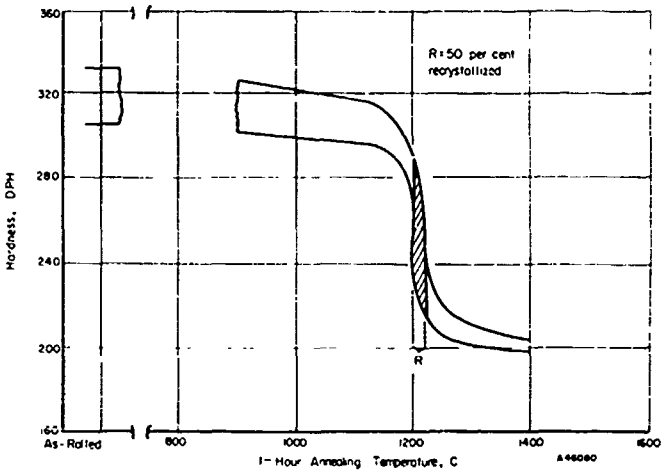


FIGURE A-116. RECRYSTALLIZATION BEHAVIOR OF POWDER-METALLURGY Mo-0.5Ti SHEET (0.040 INCH) AS DETERMINED BY HARDNESS MEASUREMENTS[31]

References

(1) Proposed Tentative Specification for Molybdenum and Molybdenum Alloy Forgings, American Society for Testing and Materials, ASTM Designation: B-62T (1962).

(2) Proposed Tentative Specification for Molybdenum and Molybdenum Alloy Billets for Reforging, American Society for Testing and Materials, ASTM Designation: B-62T (1962).

(3) Proposed Tentative Specification for Molybdenum and Molybdenum Alloy Strip, Sheet, Foil, and Plate, American Society for Testing and Materials, ASTM Designation: B-62T (1962).

(4) Proposed Tentative Specification for Molybdenum and Molybdenum Alloy Bar, Rod, and Wire, American Society for Testing and Materials, ASTM Designation: B-62T (1962).

(5) "Specification for Climelt Molybdenum - 0.5 Per Cent Titanium Forging Billets", Climax Molybdenum Co., Number CMX-FB-T-1 (May, 1961).

(6) "Specification for Climelt Molybdenum - 0.5 Per Cent Titanium Wrought Bars", Climax Molybdenum Co., Number CMX-WB-T-1 (May, 1961).

(7) "Molybdenum + 0.5% Titanium Billets", Universal Cyclops Steel Corp., Specification No. MTFB-61-2 (March 20, 1961).

(8) "Molybdenum + 0.5% Titanium Bar", Universal Cyclops Steel Corp., Specification No. MTB-61-6 (June 23, 1961).

(9) "Molybdenum + 0.5% Titanium Plate", Universal Cyclops Steel Corp., Specification No. MTP-61-3 (April 12, 1961).

(10) "Molybdenum + 0.5% Titanium Sheet", Universal Cyclops Steel Corp., Specification No. MTS-61-3 (April 12, 1961).

(11) "MTC Alloy Sheet (Mo-0.5Ti-0.03C)", Sylvania Metallurgical Products, Technical Information Bulletin.

(12) Engineering Data for the Mo-0.5 Titanium Alloy, Climax Molybdenum Co. (April, 1956).

(13) Private communication from G. D. McArdle, Climax Molybdenum Co. (1963).

(14) Kelly, C. R., "Statistical Evaluation of Mo-0.5%Ti Sheet Procured for Dyna-Soar - Final Report", Boeing Airplane Co., Contract No. AF 33(600)-41517, Document No. D2-80376 (September, 1961).

(15) Semchyshen, M., and Barr, R. Q., "Investigation of Hot-Cold Work on the Properties of Molybdenum Alloys", Climax Molybdenum Co., WADC TR 56-754 (January, 1957).

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

(17) Semchyshen, M., and Barr, R. Q., Arc-Cast Molybdenum-Base Alloys", Climax Molybdenum Co., N9onr-82100 (1955)

(18) Arc-Cast Molybdenum and Its Alloys, Climax Molybdenum Co. (1955).

(19) Semchyshen M., McArdle, G. D., and Barr, R. Q., "Development of High Strengths and High Recrystallization Temperatures in Molybdenum-Base Alloys", Climax Molybdenum Co., WADC TR 58-551 (February, 1959).

(20) Carreker, R. P., Jr., and Guard, R. W., "The Tensile Deformation of Molybdenum as a Function of Temperature and Strain Rate", Transactions of the American Institute of Metallurgical Engineers, 206, 178 (February, 1956).

(21) Semchyshen, M., McArdle, G. D., and Barr, R. Q., "Development of Molybdenum-Base Alloys", Climax Molybdenum Co., WADC TR 59-280 (October, 1959).

(22) Private communication from R. B. Bargainnier, Sylvania Electric Products, Inc. (1963).

(23) Bockris, J. O., "Electrolytic Polarisation-I. The Overpotential of Hydrogen on Some Less Common Metals at High Current Densities", Transactions of the Faraday Society, 43, 417 (1947)

(24) Kattus, J. R., Presten, J. B., and Lessley, H. L., "Investigation of Feasibility of Utilizing Available Heat-Resistant Materials for Hypersonic Leading-Edge Applications", Southern Research Institute, WADC TR 59-744, Vol. V (November, 1960).

(25) Preliminary Data, Marquardt Aircraft Co. (1959).

(26) Molybdenum Metal, Climax Molybdenum Co. (1960).

(27) Barr, R. Q., and Semchyshen, M., "Stress-Strain Curves for Wrought Molybdenum and Three Molybdenum-Base Alloys", Climax Molybdenum Co. (December, 1959).

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

(29) Preston, J. B., Roe, W. P., and Kattus, J. R., "Determination of the Mechanical Properties of Aircraft-Structural Materials at Very High Temperatures After Rapid Heating", Southern Research Institute, WADC TR 52-649, Part I (January, 1958).

(30) "Arc-Cast Molybdenum and Its Alloys, Mechanical and Elevated Temperature Properties", Universal Cyclops Steel Corp.

(31) Bargainnier, R. B., Cheney, R. F., and Tiala, L. D., "Improved Molybdenum Sheet by Powder Metallurgy Techniques", Sylvania Electric Products, Inc., Contract NOas 60-6018-c, Final Report (January 31, 1963)

(32) "Short-Time Compressive Properties of Molybdenum and Mo-0.5% Ti Alloy Bar", Universal Cyclops Steel Corp., Technical Bulletin No. 2.1.3.

(33) "Further Investigation of Notch Sensitivity of Refractory Metals", Battelle Memorial Institute, ASD-TDR-62-1004 (December, 1962).

(34) Semchyshen, M., and Barr, R. Q., "Mechanical Properties of Molybdenum and Molybdenum-Base Alloy Sheet", ASTM STP No. 272 (1959).

(35) Mueller, C. D., "Fabrication and Processing of Refractory Metals", paper presented at the AIME Symposium on Refractory Metals and Alloys, Detroit (May, 1960).

(36) Creep-Rupture Data on the 0.5% Ti-Mo Alloy at 1000 to 2400 F, Climax Molybdenum Co. (September, 1957).

(37) Freeman, R. R., "Molybdenum Base Alloys and When to Use Them", Climax Molybdenum Co. (1956).

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

(39) "Shear Strength Properties of Refractory Metal Fasteners", McDonnell Aircraft Corp., Contract No. AF 33(657)-7749 and BPSN: 2 (8-7381)-73812, Report 9346, Serial No. 3 (January 10, 1963).

(40) 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).

(41) Houck, J. A., "Review of Recent Developments - Molybdenum and Molybdenum-Base Alloys", Battelle Memorial Institute, DMIC (April 6, 1962).

(42) "Forging of Vacuum-Arc-Cast Molybdenum, Mo + 0.5% Ti, and Mo + 0.5% Ti + 0.1% Zr (TZM)", Universal Cyclops Steel Corp., Technical Bulletin No. 2.5.3 (September 25, 1962).

(43) Private communication from F. Nair, Climax Molybdenum Co. (1963).

(44) Semchyshen, M., and Barr, R. Q., "Extrusion and Mechanical Properties of Some Molybdenum- and Tungsten-Base Alloys", Climax Molybdenum Co., ASD TR 61-193 (May, 1961).

Mo-0.5Ti-0.08Zr-0.03C

1. Identification of Material

   a. Designation: TZM

   b. Chemical composition: Table A-72

   c. Forms available: billets, bars, plate and sheet[1-5]

TABLE A-72. REPRESENTATIVE ANALYSES OF ARC-CAST TZM AS PRODUCED BY CLIMAX AND UNIVERSAL CYCLOPS

Element	Content, Maximum, weight per cent		
	Climax[1-3]		Universal Cyclops[b][4]
	(a)	(b)	
Al	--	--	0.002
C	0.01-0.04	0.01-0.03	0.01-0.04
Ca	--	--	0.002
Co	--	--	0.002
Cr	--	--	0.004
Cu	--	--	0.002
Fe	0.010	0.008	0.010
H	0.0005	0.0005	0.001
K	--	--	0.001
Pb	--	--	0.002
Mg	--	--	0.002
Mn	--	--	0.002
Mo	99.25 min	99.25 min	99.34 by diff
Na	--	--	0.001
N	0.002	0.002	0.001
Ni	0.002	0.002	0.002
O	0.0025	0.0025	0.003
Si	0.008	0.008	0.020
Sn	--	--	0.004
Ti	0.40-0.55	0.40-0.55	0.40-0.55
W	--	--	0.005
Zr	0.06-0.12	0.06-0.12	0.07-0.120

(a) For forging billets and wrought bars.
(b) For sheet.

2. Physical Properties

a. Melting point: ~4730 F[5]

b. Density: 0.367 lb/in.^{3} (calculated)

3. Mechanical Properties

a. Tensile Properties at Room Temperature

Ultimate tensile strength: Tables A-73 through A-78
Figures A-117 through A-120

Tensile yield strength: Tables A-73 through A-78
Figures A-118 through A-120

Elongation: Tables A-73 through A-78
Figures A-118 through A-120

Reduction in area: Table A-77
Figure A-118

Modulus of elasticity: Table A-78

b. Effect of Temperature on Tensile Properties

Ultimate tensile strength: Tables A-79 through A-86
Figures A-121 through A-126 and A-128

Tensile yield strength: Tables A-79 through A-86
Figures A-121 through A-125 and A-128

Elongation: Tables A-79 and A-80 and A-84 through A-86
Figures A-121 through A-125 and A-127

Reduction in area: Tables A-79 and A-80
Figures A-122 and A-124

Modulus of elasticity: Tables A-84 through A-86
Figures A-121 and A-129

c. Notched Tensile Properties

Table A-87

d. Creep and Stress-Rupture Properties

Tables A-88 through A-92
Figure A-130

e. Other Selected Mechanical Properties

Hardness: Tables A-93 and A-94
Figures A-131 through A-132

Bend ductility: Table A-95
Figure A-133

TABLE A-73. ROOM-TEMPERATURE TENSILE-PROPERTY REQUIREMENTS FOR CLIMAX ARC-CAST TZM BARS[a][2]

Diameter, inches	Minimum Tensile Strength, 1000 psi	Minimum Yield Strength (0.2% Offset), 1000 psi	Minimum Elongation in 1 Inch, per cent
	Stress Relieved		
Over 13/32 to 7/8	115	100	18
Over 7/8 to 1-1/8	110	95	15
Over 1-1/8 to 1-7/8	100	85	10
Over 1-7/8 to 2-7/8	90	80	10
Over 2-7/8 to 3-1/2	85	75	5
Over 3-1/2 to 4-1/2	80	70	5
	Recrystallized		
Less than 2	80	55	20
2 to 4-1/2	75	45	10

(a) Test rate 0.002 to 0.005 inch per inch per minute through 0.6 per cent offset, then 0.02 to 0.05 inch per inch per minute to failure.

TABLE A-74. TYPICAL ROOM-TEMPERATURE TENSILE DATA FOR ARC-CAST STRESS-RELIEVED TZM ROUND BAR PRODUCED BY CLIMAX[a][6]

Diameter, inches	Average Tensile Strength, 1000 psi	Average Yield Strength (0.2% Offset), 1000 psi	Elongation in 1 Inch, per cent
1/2	134	121	27
5/8	126	121	27
3/4	127	110	27
1	128	109	25
1-1/8	122	103	25
1-1/4	115	103	22
1-1/2	110	96	20
2	104	88	19
2-3/4	96	82	21

(a) Cold Water Production Facility. All data from 6-inch-diameter arc-cast ingots covering a 2-year period. Material stress relieved 1/4 to 1 hour at 2200 to 2350 F. Test rate 0.002 inch per inch per minute in the elastic range, then 0.05 inch per inch per minute to fracture.

TABLE A-75. ROOM-TEMPERATURE TENSILE-PROPERTY REQUIREMENTS FOR UNIVERSAL-CYCLOPS ARC-CAST TZM SHEET[a][4]

Test Direction	Maximum Tensile Strength, 1000 psi	Maximum Yield Strength (0.2% Offset), 1000 psi	Minimum Elongation in 2 Inches, per cent
Longitudinal	150	140	8
Transverse	150	140	6

(a) Test rate 0.05 inch per inch per minute.

TABLE A-76. ROOM-TEMPERATURE TENSILE-PROPERTY REQUIREMENTS FOR CLIMAX ARC-CAST TZM SHEET[a][3]

Thickness, inch	Minimum Tensile Strength, 1000 psi	Minimum Yield Strength (0.2% Offset), 1000 psi	Elongation in 2 Inches, per cent
	Type 1[b]		
0.010 to 0.025, incl.	140	115	4
Over 0.025 to 0.060, incl.	135	110	5
Over 0.060 to 0.090, incl.	130	105	7
Over 0.090 to 0.187, incl.	130	105	8
	Type 2[c]		
0.010 to 0.025, incl.	120-145	100-135	6
Over 0.025 to 0.060, incl.	120-145	100-135	7

(a) Tested transverse to the final rolling direction.
(b) This type sheet is especially recommended where the highest room-temperature and elevated-temperature properties are required.
(c) This type sheet is suggested where a somewhat lower level of strength and slightly higher elongation are required in order to limit the strain hardening induced by further fabrication.

TABLE A-77. ROOM-TEMPERATURE TENSILE PROPERTIES OF TZM ROD, BAR, AND SHEET

Material	Composition (Balance Molybdenum), weight per cent	Condition	Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation, per cent	Reduction in Area, per cent
		Rod[7]				
1/2 inch	0.44Ti-0.07Zr-0.019C	As rolled	141.6	129.5	21	46
1/2 inch	0.44Ti-0.07Zr-0.019C	Stress relieved	134.3	120.5	20	35
1/2 inch	0.44Ti-0.07Zr-0.019C	Recrystallized	80.3	77.6	32	33
5/8 inch	0.46Ti-0.074Zr-0.017C	As rolled	126.9	100.4	26	59
5/8 inch	0.46Ti-0.074Zr-0.017C	Stress relieved	122.7	100.1	27	53
5/8 inch	0.46Ti-0.074Zr-0.017C	Stress relieved	129.7	100.2	29	62
5/8 inch	0.46Ti-0.074Zr-0.017C	Recrystallized	78.4	49.7	44	36
5/8 inch	0.46Ti-0.074Zr-0.017C	Recrystallized	79.7	76.5	39	38
5/8 inch	0.49Ti-0.07Zr-0.022C	Stress relieved	127.9	102.5	27	69
11/16 inch	0.49Ti-0.07Zr-0.019C	Stress relieved	119.6	104.4	29	42.8
11/16 inch	0.49Ti-0.07Zr-0.019C	Stress relieved	118.5	102.3	34	58.1
1-1/4 inch	0.49Ti-0.07Zr-0.019C	As rolled	102.6	69.2	21	28
1-1/4 inch	0.49Ti-0.07Zr-0.022C	As rolled	107.1	83.6	31	43
2 inch	0.49Ti-0.07Zr-0.022C	Stress relieved	104.4	86.4	18	17
		Bar[7]				
1 x 4 inch	0.49Ti-0.07Zr-0.019C	As rolled	110.5 (L)	90.2 (L)	13 (L)	24 (L)
1 x 4 inch	0.49Ti-0.07Zr-0.019C	As rolled	117.5 (T)	98.1 (T)	7 (T)	6 (T)
		Sheet[8]				
1/16 inch	0.5Ti-0.07Zr-0.019C	As rolled	127.3 (L)	114.9 (L)	9.5 (L)	--
1/16 inch	0.5Ti-0.07Zr-0.019C	As rolled	134.1 (T)	113.2 (T)	7.5 (T)	--
1/16 inch	0.5Ti-0.07Zr-0.019C	Stress relieved	124.3 (L)	101.4 (L)	13.5 (L)	--
1/16 inch	0.5Ti-0.07Zr-0.019C	Stress relieved	126.9 (T)	107.9 (T)	4.5 (T)	--
1/16 inch	0.5Ti-0.07Zr-0.019C	Recrystallized	70.3 (L)	70.3 (L)	41.0 (L)	--
1/16 inch	0.5Ti-0.07Zr-0.019C	Recrystallized	71.7 (T)	66.6 (T)	33.0 (T)	--
1/16 inch	0.5Ti-0.07Zr-0.054C	As rolled	128.3 (L)	120.7 (L)	12.0 (L)	--
1/16 inch	0.5Ti-0.07Zr-0.054C	As rolled	147.3 (T)	124.1 (T)	4.0 (T)	--
1/16 inch	0.5Ti-0.07Zr-0.054C	Stress relieved	102.5 (L)	--	0 (L)	--
1/16 inch	0.5Ti-0.07Zr-0.054C	Stress relieved	134.9 (T)	121.1 (T)	10.0 (T)	--
1/16 inch	0.5Ti-0.07Zr-0.054C	Recrystallized	65.9 (L)	64.1 (L)	0.5 (L)	--
1/16 inch	0.5Ti-0.07Zr-0.054C	Recrystallized	62.3 (T)	59.8 (T)	1.5 (T)	--

TABLE A-78. ROOM-TEMPERATURE TENSILE PROPERTIES OF TZM FOIL[a][9]

Thickness, inch	Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation in 2 Inches, per cent	Modulus of Elasticity, 10^6 psi
0.002	120.5	107.9	3.5	33.6
0.006	101.7 (L) 106.6 (T)	92.2 (L) 98.9 (T)	6.1 (L) 3.8 (T)	40.1 (L) 35.7 (T)
0.010	120.8	102.8	8.7	41.0

(a) Average data from five tests. Test rate 0.004 inch per inch per minute to 0.6 per cent offset, then 0.04 inch per inch per minute to failure. Analyses are given below.[10]

Thickness, inch	PPM											
	C	Si	Ti	Zr	Fe	Mo	O	N	H	Ta	W	N
0.002	290	35	4700	860	15	Bal	--	--	-	--	--	--
0.006	290	35	4300	720	15	Bal	9	2	3	100	70	10
0.010	140	35	4500	800	15	Bal	14	7	2	100	70	20

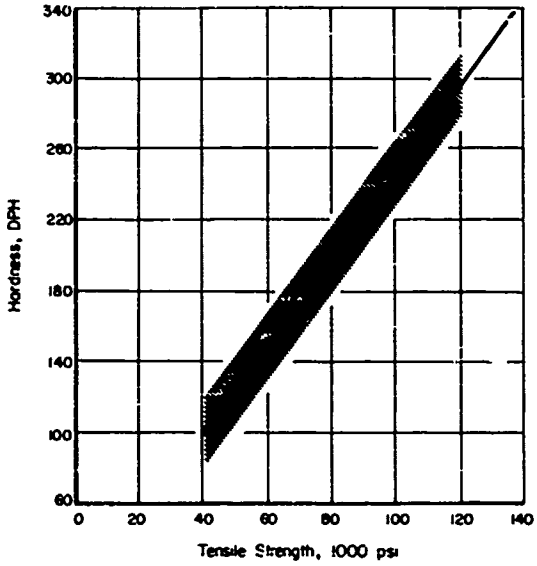


FIGURE A-117. RELATIONSHIP BETWEEN TENSILE STRENGTH AND HARDNESS OF CLIMAX ARC-CAST TZM BAR[5]

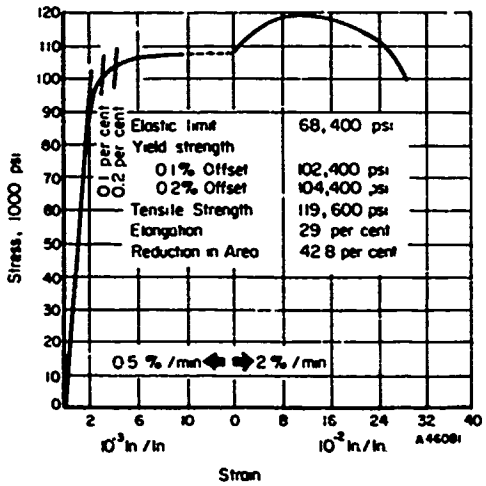


FIGURE A-118. TYPICAL ROOM-TEMPERATURE STRESS-STRAIN CURVE OF CLIMAX ARC-CAST ROLLED TZM BAR (11/16-INCH DIAMETER)[5]

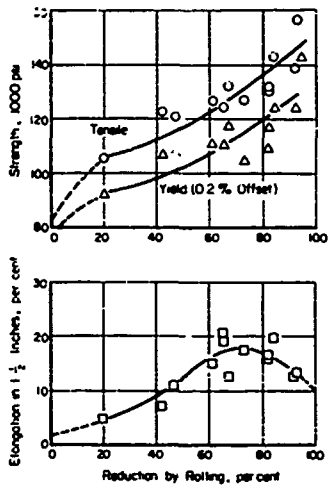


FIGURE A-119. EFFECT OF ROLLING REDUCTION ON THE ROOM-TEMPERATURE TENSILE PROPERTIES OF STRESS-RELIEVED TZM SHEET[11]

Test rate 0.001 inch per inch per second to yield, and 0.01 inch per inch per second to fracture.

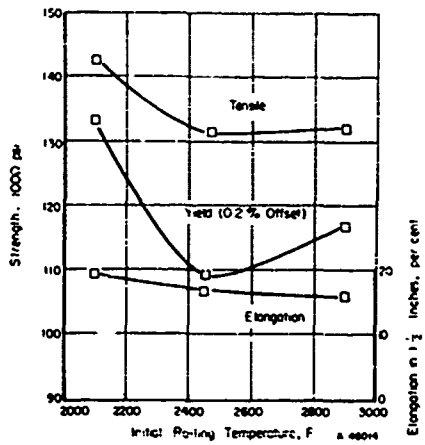


FIGURE A-120. EFFECT OF INITIAL ROLLING TEMPERATURE ON THE ROOM-TEMPERATURE TENSILE PROPERTIES OF STRESS-RELIEVED TZM SHEET[11]

TABLE A-79. TENSILE PROPERTIES OF FORGED TZM AT 3000 F[12]

Forging Temperature, F	Forging Reduction, per cent	Condition[a]	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation, per cent	Reduction in Area, per cent	Reduction in Width, per cent
1900	20	Rex	16.6	11.0	31	>100	24
	40	Rex	11.5	7.8	47	>100	36
	50	Rex	12.1	8.5	39	>100	32
	70	Rex	13.2	8.5	37	>100	32
	20	AF	12.5	9.6	33	>100	32
	40	AF	11.5	8.5	40	>100	43
	50	AF	12.0	8.4	25	>100	20
	70	AF	12.2	7.6	44	>100	48
1400	20	Rex	13.4	11.9	34	>100	32
	40	Rex	17.4	11.4	21	>100	23
	50	Rex	11.9	9.4	10	20.0	8
	60	Rex	12.7	9.6	36	>100	40
	20	AF	13.8	11.4	21	>100	24
	40	AF	12.6	8.4	29	>100	24
	50	AF	12.7	10.0	35	>100	37

(a) Rex = recrystallized
AF = as forged.

TABLE A-80. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF TZM ROD AND SHEET

Size, inch	Composition (Balance Molybdenum), weight per cent	Condition	Temperature, F	Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation per cent	Reduction in Area, per cent
			Rod[7]				
1/2	0.44Ti-0.07Zr-0.019C	As rolled	1600	88.4	46.3	21	46
1/2	0.44Ti-0.07Zr-0.019C	Stress relieved	1600	82.6	52.7	15	74
1/2	0.44Ti-0.07Zr-0.019C	Recrystallized	1600	32.5	5.5	36	87
5/8	0.46Ti-0.074Zr-0.017C	Stress relieved	1800	85.5	--	18	73
5/8	0.46Ti-0.074Zr-0.017C	Recrystallized	1800	41.7	17.9	35	62
11/16	0.49Ti-0.07Zr-0.019C	Stress relieved	1800	76.1	66.3	18	66
11/16	0.49Ti-0.07Zr-0.019C	Stress relieved	1800	77.3	75.4	15	71.3
11/16	0.49Ti-0.07Zr-0.019C	Stress relieved	2000	73.1	67.7	17	80.8
11/16	0.49Ti-0.07Zr-0.019C	Stress relieved	2000	71.4	63.8	18	85.4
5/8	0.46Ti-0.074Zr-0.019C	Stress relieved	2400	53.9	--	31	96
5/8	0.46Ti-0.074Zr-0.019C	Recrystallized	2400	23.4	--	69	96
11/16	0.49Ti-0.07Zr-0.019C	Stress relieved	2400	54.4	42.0	26	91.6
11/16	0.49Ti-0.07Zr-0.019C	Stress relieved	2400	53.5	39.3	29	93.3
5/8	0.46Ti-0.074Zr-0.019C	Rolled and swaged	3000	14.05	--	50	99
5/8	0.46Ti-0.074Zr-0.019C	Rolled and swaged	3500	4.18	--	66	99
			Sheet[8]				
1/16	0.5Ti-0.07Zr-0.019C	As rolled	1800	79.6 (L)	--	5.0 (L)	--
1/16	0.5Ti-0.07Zr-0.019C	As rolled	1800	84.5 (T)	--	1.0 (T)	--
1/16	0.5Ti-0.07Zr-0.054C	As rolled	1800	79.8 (L)	43.4 (L)	10.0 (L)	--
1/16	0.5Ti-0.07Zr-0.054C	As rolled	1800	83.3 (T)	50.9 (T)	1.5 (T)	--
1/16	0.5Ti-0.07Zr-0.019C	Stress relieved	1800	79.6 (L)	--	4.0 (L)	--
1/16	0.5Ti-0.07Zr-0.019C	Stress relieved	1800	82.4 (T)	--	9.0 (T)	--
1/16	0.5Ti-0.07Zr-0.054C	Stress relieved	1800	83.4 (L)	52.0 (L)	10.0 (L)	--
1/16	0.5Ti-0.07Zr-0.054C	Stress relieved	1800	89.2 (T)	74.1 (T)	2.0 (T)	--
1/16	0.5Ti-0.07Zr-0.019C	Recrystallized	1800	45.5 (L)	--	18.0 (L)	--
1/16	0.5Ti-0.07Zr-0.019C	Recrystallized	1800	41.6 (T)	--	14.0 (T)	--
1/16	0.5Ti-0.07Zr-0.054C	Recrystallized	1800	39.2 (L)	15.0 (L)	14.0 (L)	--
1/16	0.5Ti-0.07Zr-0.054C	Recrystallized	1800	37.7 (T)	15.8 (T)	12.0 (T)	--
1/16	0.5Ti-0.07Zr-0.019C	Stress relieved	2400	39.3 (L)	--	9.0 (L)	--
1/16	0.5Ti-0.07Zr-0.019C	Stress relieved	2400	46.6 (T)	--	13.0 (T)	--
1/16	0.5Ti-0.07Zr-0.054C	Stress relieved	2400	27.9 (L)	--	26.5 (L)	--
1/16	0.5Ti-0.07Zr-0.054C	Stress relieved	2400	30.4 (T)	--	18.0 (T)	--
1/16	0.5Ti-0.07Zr-0.019C	Recrystallized	2400	22.1 (L)	7.9 (L)	26.0 (L)	--
1/16	0.5Ti-0.07Zr-0.019C	Recrystallized	2400	22.9 (T)	10.6 (T)	32.0 (T)	--
1/16	0.5Ti-0.07Zr-0.054C	Recrystallized	2400	17.3 (L)	10.6 (L)	61.5 (L)	--
1/16	0.5Ti-0.07Zr-0.054C	Recrystallized	2400	20.3 (T)	10.7 (T)	51.0 (T)	--

TABLE A-81. TENSILE-PROPERTY REQUIREMENTS FOR CLIMAX TYPE 1 ARC-CAST TZM SHEET AT 2200 F[a][3]

Thickness, inch	Minimum Tensile Strength, 1000 psi	Minimum Yield Strength (0.2% Offset), 1000 psi	Minimum Elongation in 1 Inch, per cent
0.010 to 0.025, incl.	50	25	5
Over 0.025 to 0.060, incl.	50	25	6
Over 0.060 to 0.090, incl.	50	25	8
Over 0.090 to 0.187, incl.	50	25	10

(a) Tested transverse to the final rolling directions Type 1 sheet is especially recommended where the highest room-temperature and elevated-temperature properties are required.

TABLE A-82. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF SYLVANIA POWDER-METALLURGY TZM SHEET[13]

Temperature, F	Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation, per cent
	0.060 Inch[a]		
RT	131	117	14
	128	113	>10
2400	54	48	12
	61	53	7
3000	9	5	61
	10	8	59
	0.040 Inch		
2400	65	59	6
	72	68	7

(a) Annealed 1 hour at 2730 F.

TABLE A-83. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF STRESS-RELIEVED TZM SHEET (0.045 INCH)[a][14]

Temperature, F	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation in 3/4 Inch, per cent
RT	124.5	113.5	15
	143.5	129.9	12.5
1000	92.1	85.5	6.2
	92.4	86.8	7.5
1600	83.1	70.6	5.0
	87.5	--	11.2
2200	54.6	47.7	10.6
	43.6	34.0	2.5
2500	21.8	13.6	48.8
	31.8	26.6	15.0

(a) Stress relieved 1 hour at 2200 F. Test rate 0.005 inch per inch per minute to yield, then 0.03 inch per inch per minute to fracture. Nominal carbon content 0.04 per cent.

TABLE A-84. SUMMARY OF IMPORTANT CONVERSION VARIABLES FOR TZM SHEET DATA PRESENTED IN TABLE A-86

	Conversion Variables							
Sheet Identity	Forging Techniques	Initial Rolling Temperature, F	Final Rolling Temperature, F	Number Inter-mediate Anneals	Reduction After Last Recrystal-lization, per cent	Sheet Thickness, inch	Heat-Treat Condition[a]	Hardness[b], DPH
A-1	Upset	2460	1830	3	65	0.080	Stress relieved	290
A-2	Upset	2460	1830	3	65	0.080	Recrystallized	196
A-3	Upset	2460	1830	3	65	0.080	As-rolled	287
B-1	Upset	2460	2100	3	82	0.040	Stress relieved	308
B-2	Upset	2460	2100	3	82	0.040	Recrystallized	195
B-3	Upset	2460	2100	3	82	0.040	As-rolled	301
C-1	Bust & Draw	2460	2460	4	20	0.120	Stress relieved	242
C-2	Bust & Draw	2460	2460	4	20	0.120	Recrystallized	229
C-3	Bust & Draw	2460	2460	4	20	0.120	As-rolled	247
C-4	Bust & Draw	2460	2460	4	73	0.040	Stress relieved	292
C-5	Bust & Draw	2460	2460	4	73	0.040	Recrystallized	216
D-1	Bust & Draw	2900	2900	1	--	0.080	As-rolled	299
D-2a	Bust & Draw	2900	2100	3	17	0.120	Stress relieved	261
D-2b	Bust & Draw	2900	2100	3	65	0.080	Stress relieved	291
D-2c	Bust & Draw	2900	2100	3	82	0.040	Stress relieved	301
EH-1	Bust & Draw	2100	2100	2	84	0.088	Stress relieved	325
EH-2	Bust & Draw	2100	2100	2	93	0.040	Stress relieved	324
EH-3	Bust & Draw	2100	2100	2	93	0.040	Recrystallized	261
EGA	Bust & Draw	2900	2100	2	67	0.063	Stress relieved	298
EGB	Bust & Draw	2900	2100	2	61	0.078	Stress relieved	279
EGC	Bust & Draw	2900	2100	2	42	0.117	Stress relieved	278
EGX	Bust & Draw	2900	--	1	92	0.040	Stress relieved	314

(a) Stress relieved 1 hr at 1900 F in hydrogen. Recrystallized 1 hr at 2525 F in hydrogen
(b) 1000-gram load.

TABLE A-85. INTERSTITIAL ANALYSES FOR TZM SHEET DATA PRESENTED IN TABLE A-86

	Gas Contents (ppm)		
Sheet Identity	Oxygen	Hydrogen	Nitrogen
A-1	16.0	0.9	10
B-1	27.0	0.8	13
C-1	5.7	0.5	25
C-4	9.5	4.3	15
D-1	62.0	1.3	9
D-2c	2.8	0.5	9
EGA	36.0	0.5	11
EGX	4.3	3.6	12
EH-1	5.5	0.1	9

TABLE A-86. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF TZM SHEET[a][11]

Sheet Identity	Temperature, F	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation in 1.5 Inches, per cent	Modulus of Elasticity, 10^6 psi
			Series A		
A-1	RT	123.4	109.9	20	39.0
A-1		124.0	110.2	21	37.0
A-2		86.0	--	--	38.0
A-2		85.9	82.2	--	40.0
A-3		139.8	121.4	16	39.0
A-3		140.8	121.0	17	38.0
A-1	1000	80.5	72.0	7	33.0
A-2		45.6	21.5	25	26.0
A-3		93.9	86.3	6	32.5
A-1	1500	76.1	69.5	4.5	35.0
A-2		42.2	20.0	23	22.0
A-1	2000	67.1	60.5	4.5	28.0
A-1		69.0	63.1	6	29.0
A-2		35.2	18.4	20	19.3
A-3		74.8	68.2	5	29.0
A-1	2500	24.4	12.6	18	18.5
A-2		26.6	16.0	18	16.4
A-1	3000	14.7	7.9	24	10.0
A-1		13.0	6.9	25	8.9
A-2		12.0	7.5	27	10.3
A-3		14.0	10.0	23	--
			Series B		
B-1	RT	132.2	108.4	16	42.4
B-1		131.2	119.0	17	41.3
B-1[b]		146.0	128.0	15	40.0
B-1[b]		146.0	132.0	14	40.0
B-2		96.1	72.5	19	43.3
B-2		97.0	69.8	17	41.3
B-3		152.5	122.8	13	41.3
B-3		136.1	118.3	17	45.4
B-1	1000	95.8	86.0	3.5	39.5
B-1		96.2	86.0	5	38.0
B-2		59.3	24.5	24	37.5
B-3		103.6	95.8	2.5	38.7
B-1	1500	88.8	82.1	3	35.0
B-1		89.0	81.0	3	38.0
B-1		94.0	88.5	3.5	39.0
B-2		45.0	23.9	17	35.0
B-2		37.5	20.0	16	36.0
B-3		75.5	69.0	3.5	35.0
B-3		90.2	83.9	4	38.0

TABLE A-86. (Continued)

Sheet Identity	Temperature, F	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation in 1.5 Inches, per cent	Modulus of Elasticity, 10^6 psi
		Series B (Continued)			
B-1	2000	74.6	68.9	4	29.0
B-1[b]		85.2	77.1	4	31.0
B-1[b]		78.0	68.3	5	30.0
B-2		33.0	21.0	14	22.0
B-3		71.2	61.0	5.5	24.0
B-1	2500	35.2	28.8	10	22.5
B-1		27.0	19.5	12	20.0
B-2		25.0	16.8	20	18.5
B-2		25.0	17.1	16	22.0
B-3		36.0	32.0	18	17.3
B-3		42.8	39.0	5	19.0
B-1	3000	14.0	8.7	24	13.6
B-1		13.2	8.5	34	14.0
B-2		16.0	11.1	21	12.3
B-3		13.1	8.6	23	10.0
		Series C			
C-1	RT	107.0	--	3	43.1
C-1		105.0	92.6	8	44.3
C-2		75.0	--	2	41.0
C-2		84.0	79.1	1	45.7
C-3		111.0	97.0	10	41.8
C-3		110.0	97.3	4	44.0
C-4		125.0	102.0	20	46.1
C-4		128.0	105.0	15	43.6
C-5		99.4	68.1	27	45.4
C-5		102.0	71.8	--	40.2
C-1	1000	61.5	57.0	12	40.0
C-2		58.0	50.8	14	37.0
C-3		74.8	73.1	8.7	36.0
C-4		89.3	82.2	4	39.0
C-5		46.0	26.8	20	36.0
C-1	1500	56.2	53.8	11.3	35.5
C-2		52.0	46.2	12.7	34.0
C-4		82.7	76.0	5	37.5
C-5		43.9	22.5	21	32.8
C-1	2000	48.4	45.5	12	30.0
C-2		45.0	40.3	13.3	29.5
C-3		56.1	54.1	13	23.7
C-4		68.9	61.8	4.6	31.0
C-5		38.3	21.2	26	30.0

TABLE A-86. (Continued)

Sheet Identity	Temperature, F	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation in 1.5 Inches, per cent	Modulus of Elasticity, 10^6 psi
		Series C (Continued)			
C-1	2500	38.0	34.6	14.7	28.0
C-1		39.4	35.7	15.3	28.0
C-2		36.8	32.2	14.7	24.0
C-3		33.0	33.0	--	21.2
C-3		43.2	42.0	13	29.5
C-4		25.8	15.8	16.7	26.0
C-5		27.1	16.2	20	24.5
C-1	3000	17.3	12.0	20	10.5
C-2		17.0	10.9	24	14.5
C-3		18.6	14.4	19	12.5
C-4		15.0	8.1	25	16.0
C-5		18.8	11.5	19	12.8
		Series D			
D-1	RT	122.0	119.0	1.3	42.0
D-1		122.0	118.0	--	40.0
D-2a		126.0	110.5	2	45.0
D-2a		122.0	106.0	19.0	37.0
D-2b		124.5	110.0	19.0	42.5
D-2b[b]		134.0	125.5	10.0	39.8
D-2b[b]		137.0	122.0	17.0	39.8
D-2c		132.0	118.0	17.0	42.0
D-2c		132.0	117.0	15.0	42.0
D-1	1000	76.0	71.5	7.3	36.0
D-2a		83.5	78.0	8.3	39.0
D-2b		84.0	76.0	8.3	33.0
D-2c		91.0	82.0	6.0	33.5
D-1	1500	77.9	76.9	4.3	30.5
D-1		75.0	72.0	5.7	30.5
D-2a		79.4	74.7	9.3	30.8
D-2b		78.2	72.0	8.3	32.0
D-2c		84.7	78.0	4.0	35.0
D-2c		85.5	79.0	3.3	32.0
D-1	2000	63.7	60.9	6.7	26.0
D-1		65.0	60.5	5.0	29.0
D-2a		67.2	63.2	8.0	28.0
D-2b		66.3	60.0	8.0	30.0
D-2c		74.7	67.3	5.0	30.0
D-2c		73.0	67.0	9.3	26.5
D-1	2500	50.0	44.1	6.7	25.0
D-1		49.2	44.1	7.3	24.0
D-1		50.0	44.2	7.3	24.5
D-2a		55.8	51.8	10.0	24.2
D-2b		48.5	41.6	9.7	24.5
D-2b		48.2	42.1	10.6	24.0

TABLE A-86. (Continued)

Sheet Identity	Temperature, F	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation in 1.5 Inches, per cent	Modulus of Elasticity, 10^6 psi
		Series D (Continued)			
D-2c	2500	30.0	21.8	12.0	24.0
D-2c		54.2	46.3	5.8	23.0
D-2c		43.0	36.2	7.3	21.0
D-1	3000	15.8	9.4	15	9.2
D-1		14.6	9.0	14	12.7
D-2a		17.0	10.5	25	9.8
D-2b		15.6	9.6	14	13.5
D-2c		15.3	9.4	13.5	14.2
D-2c		15.0	9.1	14.3	13.1
		Series EH			
EH-1	RT	143.0	124.0	19	39.0
EH-1		142.0	123.0	20	44.0
EH-1		144.0	125.0	19	40.5
EH-2		160.0	151.0	9	40.5
EH-2		153.0	136.0	17	37.5
EH-3		104.0	81.0	30	40.0
EH-3		100.0	78.0	27	40.5
EH-1	1000	105.0	94.0	6.7	38.5
EH-2		120.0	110.0	2.7	39.0
EH-3		52.1	27.5	21.3	37.8
EH-1	1500	93.0	86.4	6.7	31.0
EH-2		102.0	94.7	3.3	33.0
EH-3		47.9	25.5	23.3	28.0
EH-1	2000	81.8	74.5	6.0	24.0
EH-1		88.5	81.9	6.0	26.0
EH-2		88.3	76.2	3.1	28.0
EH-2		88.2	78.0	3.8	24.0
EH-3		41.0	24.9	15.3	23.6
EH-3		40.8	25.0	13.4	24.4
EH-1	2500	58.9	50.4	7.3	17.3
EH-1		41.0	34.8	9.3	15.0
EH-2		47.5	40.9	5.3	15.5
EH-2		50.5	41.9	5.3	15.8
EH-3		26.3	16.8	16.0	14.0
EH-3		22.0	13.5	18.6	13.3
EH-1	3000	14.4	8.9	27.3	11.0
EH-1		14.0	8.7	26.7	10.2
EH-2		16.4	10.1	24.5	6.5
EH-3		12.8	8.2	23	6.5

TABLE A-86. (Continued)

Sheet Identity	Temperature, F	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation in 1.5 Inches, per cent	Modulus of Elasticity, 10^6 psi
			Series EG		
EGA	RT	132.0	117.0	13	38.7
EGA		132.0	118.0	12	40.0
EGB		127.0	112.0	--	39.1
EGB		126.0	110.0	15	40.0
EGC		123.0	107.5	7.0	--
EGA	1000	92.7	83.8	5.3	37.9
EGB		90.0	83.0	7.5	32.0
EGA	1500	85.0	78.5	4	32.1
EGB		78.8	74.0	7	26.0
EGC		80.2	78.0	9.5	34.0
EGA	2000	73.0	66.3	4	26.0
EGA		86.1	80.1	3.9	25.7
EGB		76.2	70.9	7	26.5
EGC		72.5	68.0	6	28.0
EGA	2500	60.8	52.8	5.3	15.6
EGA		56.0	47.5	5.3	14.0
EGB		63.9	56.4	5	21.8
EGC		37.8	33.0	12	20.3
EGA	3000	15.0	9.4	26	6.5
EGB		15.2	9.0	20	11.0
			Series EGX		
EGX	RT	136.0	122.0	13	40.0
		139.0	124.0	14	40.2
		142.0	126.0	12	37.8
		146.0	130.0	16	40.5
		142.0	128.0	13	40.0
		140.0	125.0	14	40.5
EGX	1000	101.0	93.1	3.3	37.2
		99.8	91.0	3.3	39.0
EGX	1500	95.9	89.0	2.7	34.0
		92.0	86.6	3.0	35.0
EGX	2000	77.3	66.8	3.7	25.7
		82.5	75.0	3.7	28.2
		80.0	73.9	2.8	26.0
		80.0	73.9	3.0	28.8
EGX	2500	51.0	45.2	3.9	16.3
		59.5	52.0	3.8	17.9
		57.3	51.4	3.3	19.0
		46.5	41.4	4.5	13.2

TABLE A-86. (Continued)

Sheet Identity	Temperature, F	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation in 1.5 inches, per cent	Modulus of Elasticity, 10^6 psi
		Series EGX (Continued)			
EGX	3000	16.5	9.6	24.7	6.6
		15.2	8.9	25.3	9.9

(a) Test Conditions:

Atmosphere	Argon-7% hydrogen
Hold Time at Temperature	5 min
Strain Rate to YS	0.001 in./in./sec
Strain Rate From YS to UTS	0.01 in. in./sec
Method of Heating	Resistance

(b) Transverse.

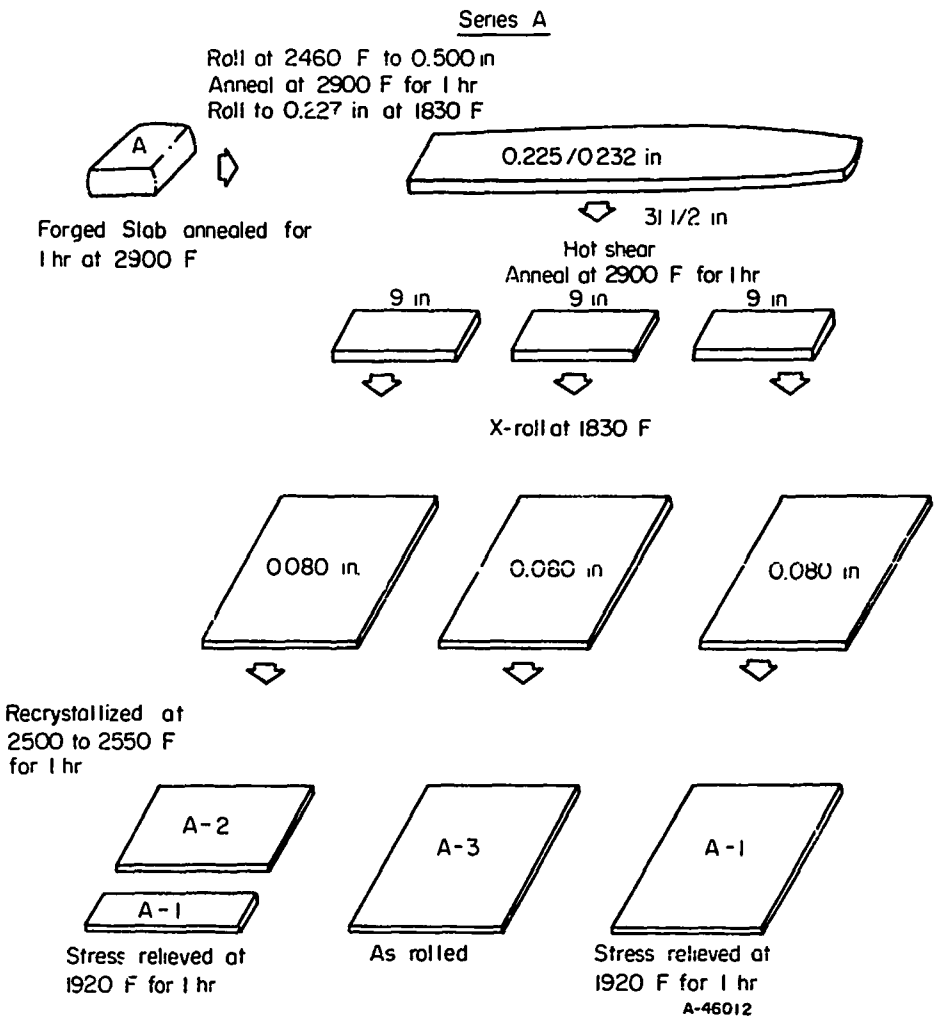


FIGURE A-121. FABRICATION HISTORY FOR TZM SHEET FOR WHICH DATA ARE PRESENTED IN TABLE B-6-15

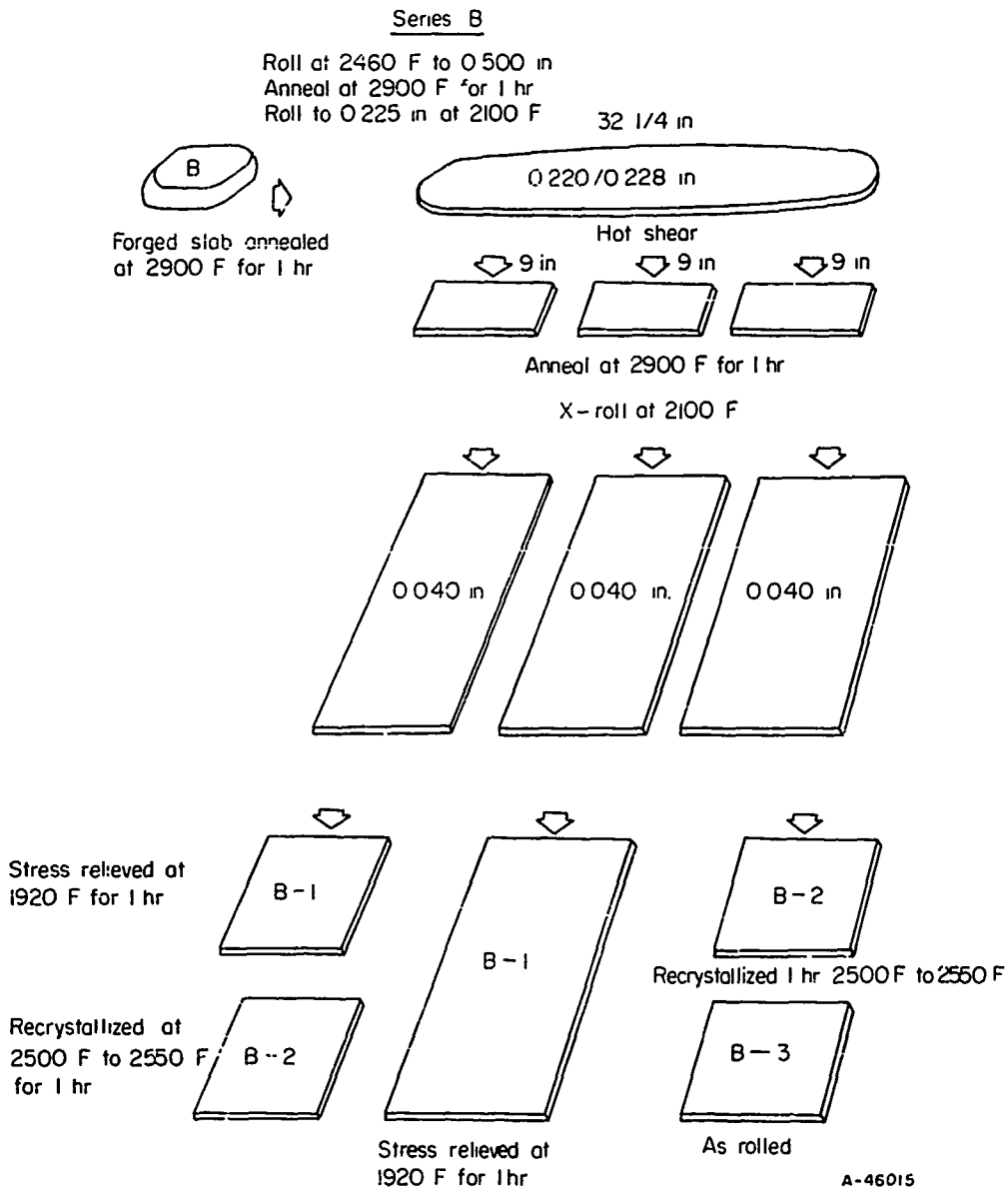


FIGURE A-121. (CONTINUED)

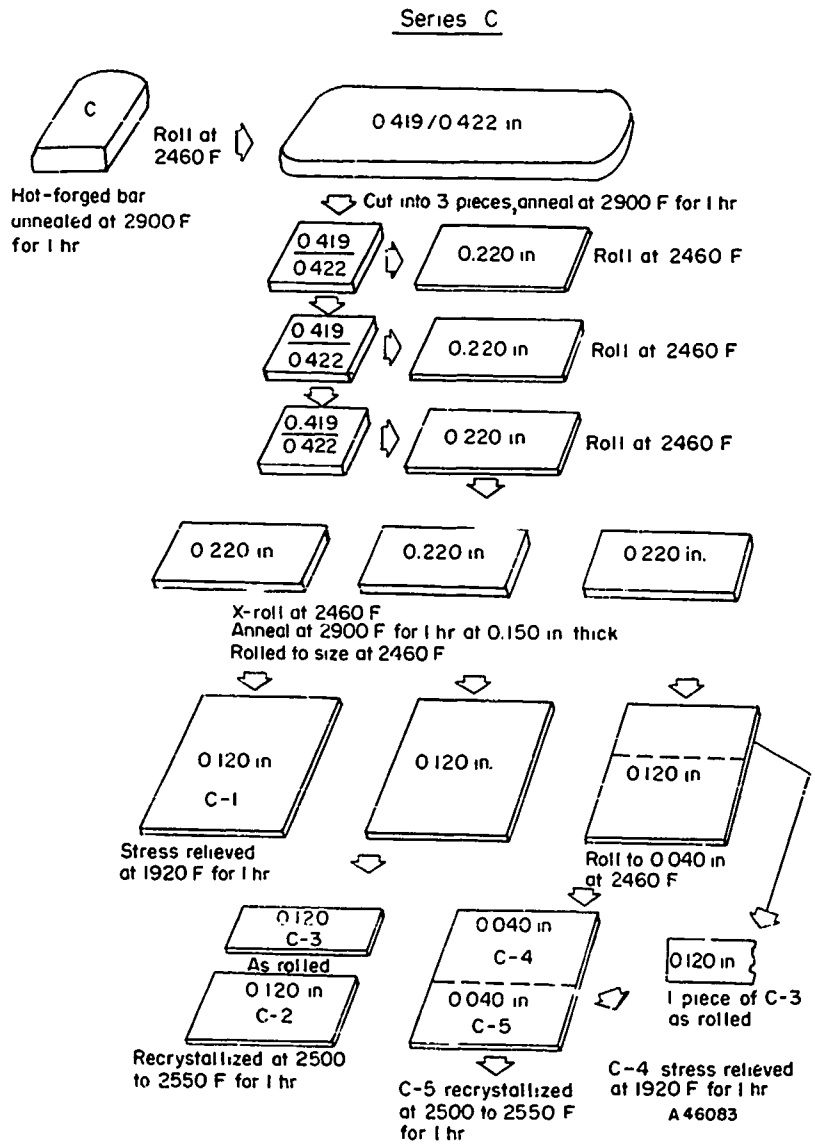


FIGURE A-121. (CONTINUED)

Series D

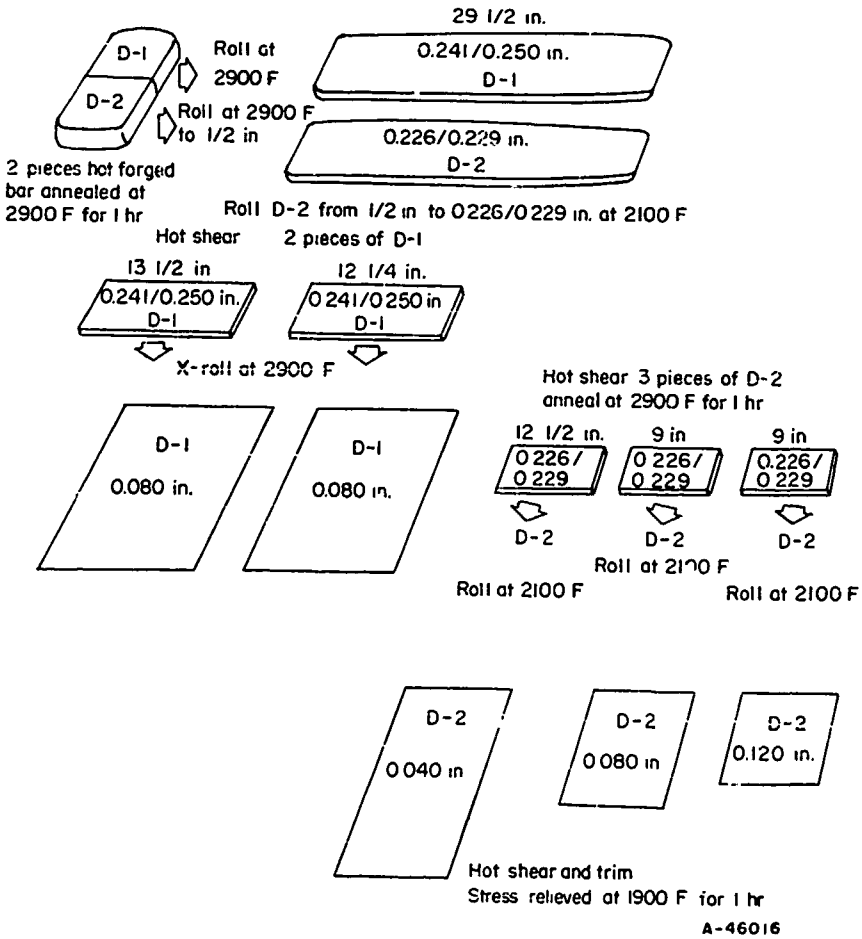


FIGURE A-121. (CONTINUED)

Series EH

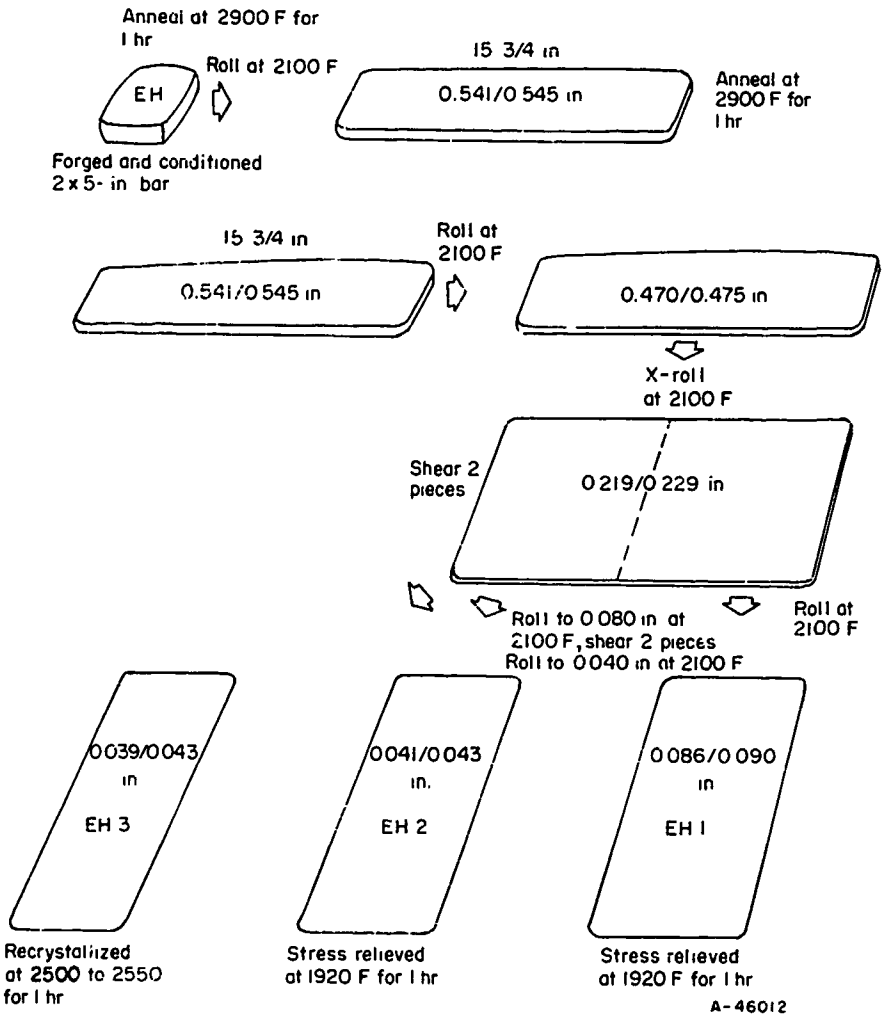


FIGURE A-121. (CONTINUED)

Series EG

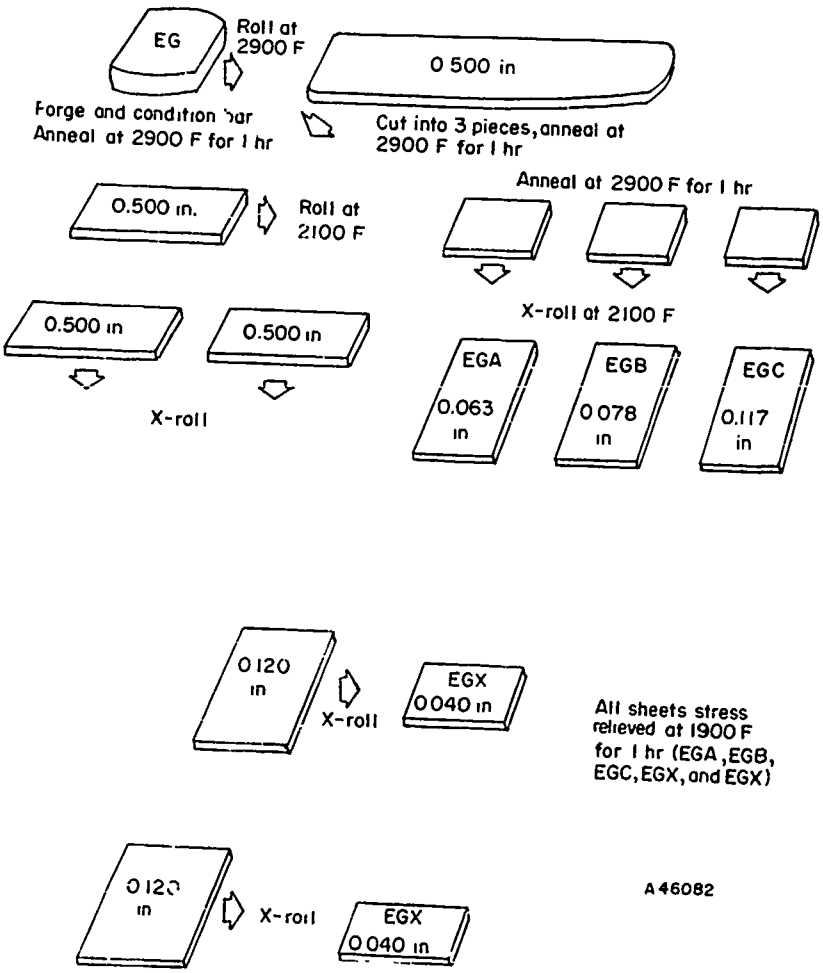


FIGURE A-121. (CONTINUED)

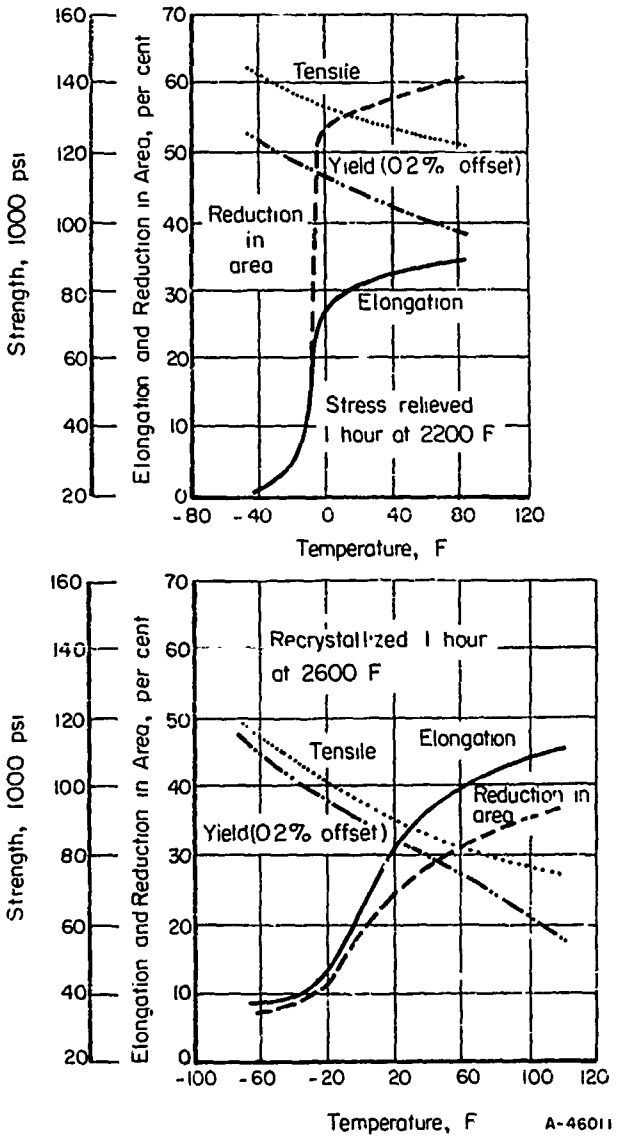


FIGURE A-122. LOW-TEMPERATURE TENSILE PROPERTIES OF CLIMAX ARC-CAST STRESS-RELIEVED AND RECRYSTALLIZED TZM BAR (5/8-INCH DIAMETER)[5]

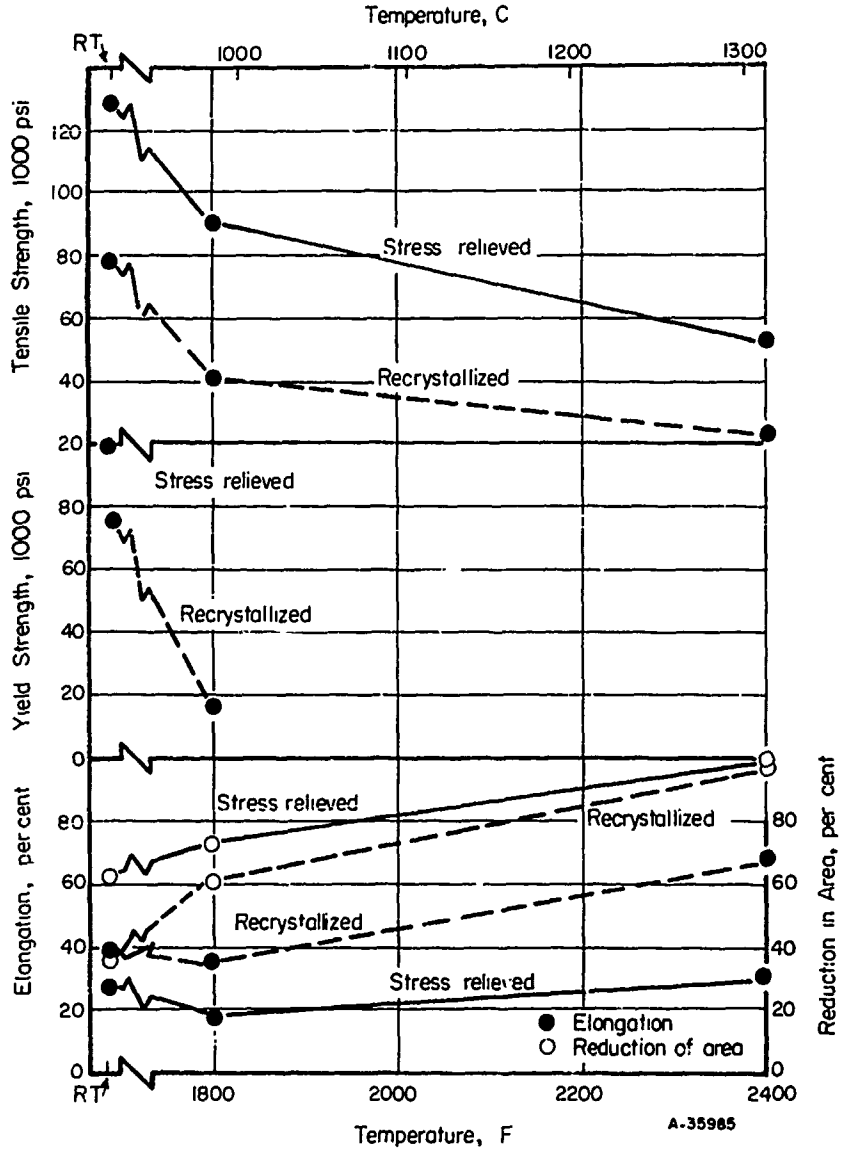


FIGURE A-123. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF TZM[15]

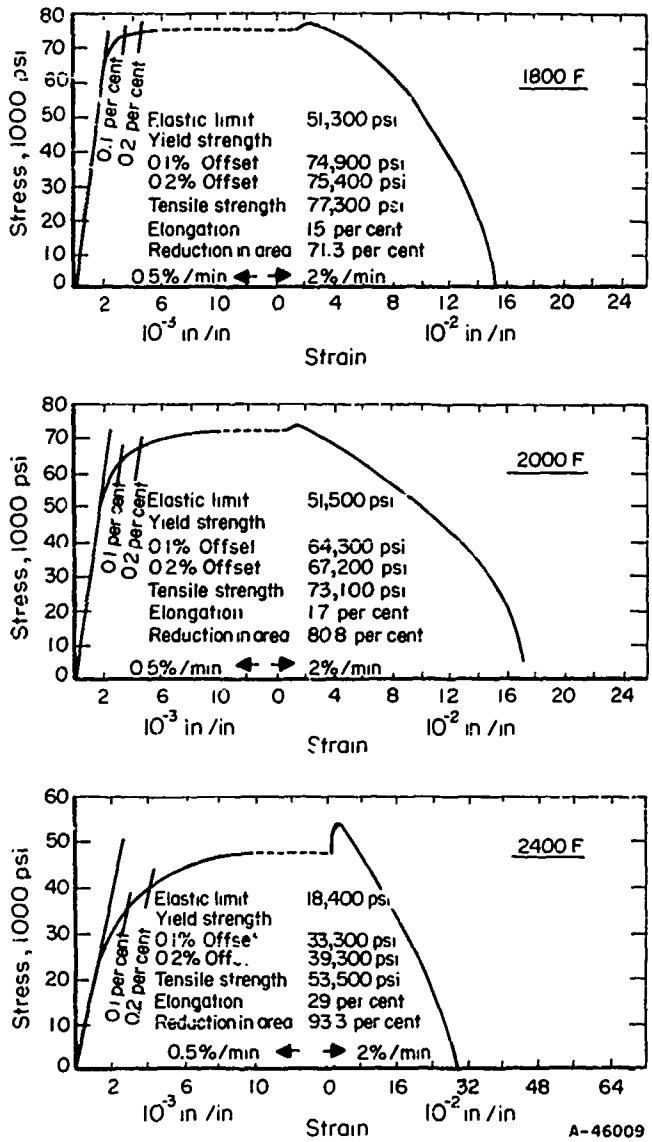


FIGURE A-144. TYPICAL STRESS-STRAIN CURVES OF CLIMAX ARC-CAST ROLLED TZM BAR (11/16-INCH DIAMETER)[5]

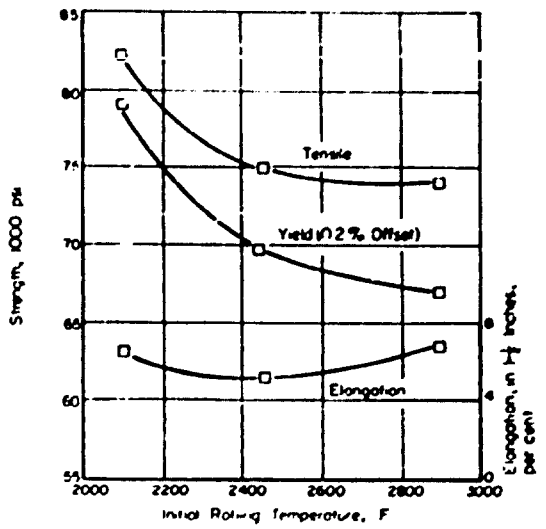


FIGURE A-125. EFFECT OF INITIAL ROLLING TEMPERATURES ON THE TENSILE PROPERTIES OF STRESS-RELIEVED TZM SHEET AT 2000 F[11]

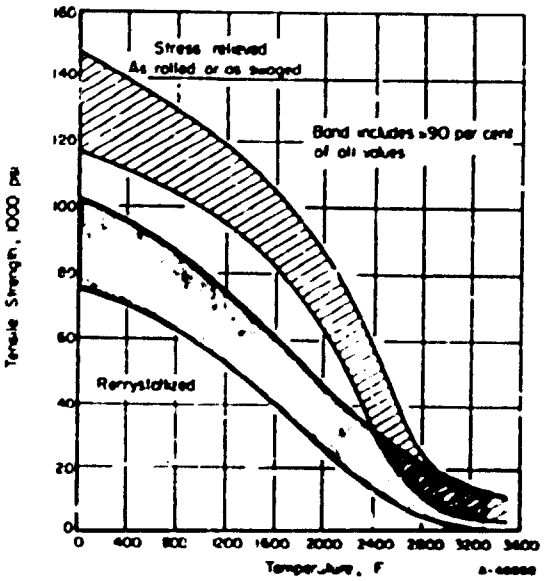


FIGURE A-126. EFFECT OF TEMPERATURE ON THE TENSILE-STRENGTH RANGE OF CLIMAX ARC-CAST TZM BAR AND SHEET[5]

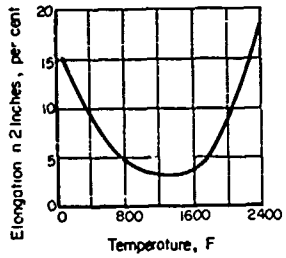


FIGURE A-127. EFFECT OF TEMPERATURE ON THE ELONGATION OF STRESS-RELIEVED TZM SHEET[5]

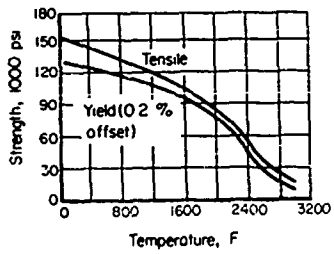


FIGURE A-128. EFFECT OF TEMPERATURE ON THE STRENGTH OF STRESS-RELIEVED TZM[6]

Test rate 0.05 inch per inch per minute.

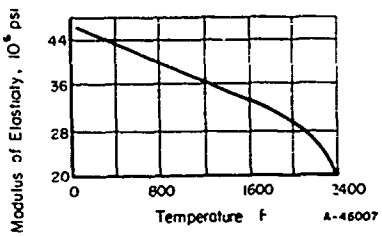


FIGURE A-129. EFFECT OF TEMPERATURE ON THE MODULUS OF ELASTICITY OF TZM[17]

Analyses 0.49% Ti, 0.071% Zr, and 0.019% C.

TABLE A-87. ROOM-TEMPERATURE NOTCHED TENSILE PROPERTIES OF STRESS-RELIEVED TZM SHEET[a][14]

Notch Radius, inch	Notch Width, inch	Sheet Thickness, inch	K_t	Notched Tensile Strength, 1000 psi	Elongation in 3/4 Inch, per cent	Notched Tensile Strength/Unnotched Tensile Strength Ratio
0.013	0.384	0.044	4.1	142.0	1.2	1.06
0.013	0.385	0.044	4.1	139.0[b]	--	--
0.003	0.417	0.054	8.3	136.0	3.0	1.01
0.003	0.417	0.054	8.3	135.5	2.0	1.0

(a) Stress relieved 1 hour at 2200 F. Test rate 0.005 inch per inch per minute to yielding, then 0.03 inch per inch per minute to fracture. Nominal carbon content 0.04 per cent.
(b) Fracture occurred in loading pinhole.

TABLE A-88. STRESS-RUPTURE DATA FOR STRESS-RELIEVED AND RECRYSTALLIZED TZM SHEET (1/16 INCH) AT 1800 F[a][8]

Condition	Stress, 1000 psi, to Produce Rupture		
	1 Hour	10 Hours	100 Hours
Stress relieved 1 hour at 2200 F	73.0	67.0	60.5
Recrystallized 1 hour at 2650 F	46.0	40.0	35.0

(a) Carbon content 0.019 per cent.

TABLE A-89. CREEP AND STRESS-RUPTURE PROPERTIES OF STRESS-RELIEVED AND RECRYSTALLIZED TZM AT 1800 AND 2400 F[a][18]

Condition	Temperature, F	Stress, 1000 psi	Creep Rate, per cent/hour	Rupture Time, hours	Elongation, per cent	Reduction in Area, per cent
Stress relieved	1800	85.0	0.34	11.0	16.0	74.0
		80.0	0.08	65.3	17.3	75.3
	2400	35.0	1.50	2.6	26.1	81.9
		27.0	0.44	4.0	27.9	89.9
Recrystallized	1800	40.0	0.005	334.1[b]	8.4	--
		35.0	0.004	470.6[b]	3.7	--
	2400	20.0	0.90	15.0	41.7	92.3
		16.0	0.46	32.9	37.0	86.8

(a) Analyses 0.40% Ti, 0.08% Zr, and 0.08% C.
(b) Test discontinued.

TABLE A-90. CREEP AND STRESS-RUPTURE PROPERTIES OF CLIMAX ARC-CAST TZM BAR AND SHEET AT 1800 TO 3000 F[5]

Material	Condition	Temperature, F	Stress, 1000 psi	Minimum Creep Rate, per cent/hr	Rupture Time, hours	Elongation, per cent	Reduction in Area, per cent
Bar, 1/2-inch diameter	Stress relieved, 2200 F	1800	70	0.13	18.6	14	98
			70	0.033	59.6	13	73
			72	0.03	79.0	15	78
			77	0.09	32.5	15	83
	Recrystallized		37	0.005	256.5[a]	8	--
			40	--	(b)	35	93
			40	2.5	7.5	29	90
			40	0.037	51.5	25	66
			45	--	0.1	35	92
Sheet, 1/16 inch	Stress relieved, 2200 F		65	0.13	20.0	6	--
			75	--	0.1	6	--
	Recrystallized		30	nil	326.1[a]	3	--
			35	0.045	95.1	16	--
			40	1.1	10.9	24	-
			45	--	(b)	29	--
Bar, 1/2-inch diameter	Stress relieved[c]	2000	50	0.001	132.6	12	56
			55	--	143.2[a]	3	1
			60	0.018	23.9	18	84
			65	--	6.2	25	46
	Recrystallized		27	0.059	213.8	27	67
			30	--	119.5	34	96
			33	0.07	44.0	28	66
			34	--	10.8	24	76
Bar, 1/2-inch diameter	Stress relieved, 2300 F	2400	14	--	40.0	55	95
			22	--	10.1	25	96
			32	--	3.5	21	88
	Recrystallized		14	--	40.2	57	95
			18	--	26.3	40	97
			20	--	16.1	66	97
Bar, 3/4-inch diameter	Recrystallized	3000	3.5	0.07	24.0	89	99
			5.0	2.2	3.95	90	99

(a) Test discontinued.
(b) On loading.
(c) First and third tests – 2200 F; other two – 2300 F.

Note: The following stress-rupture strengths are derived from these data.

	100-Hour Rupture Strength, 1000 psi			
	1800	2000	2400	3000 F
Bar				
Stress relieved	70	54	10E	--
Recrystallized	39	30	10E	2.7E[a]
Sheet				
Stress relieved	60E	--	--	--
Recrystallized	35	--	--	--

(a) E – extrapolated on basis of available data.

TABLE A-91. CREEP PROPERTIES OF TZM SHEET SERIES A-1[a, b](11)

Temperature, F	Stress, 1000 psi	Loading Strain, per cent	Time, sec, to Produce Indicated Plastic Creep						Elongation in 1.5 Inches, per cent
			.05%	0.2%	0.5%	1%	2%	4%	
2000	55	0.2	7.5	123	1747	--	--	--	8.7
2500	12	0.03	32	950	3600	--	--	--	14.6
	15	0.07	7.4	93	217	415	768	2120	24.0
3000	6	--	61	245	767	1096	1600	2978	24.7
	7	0.07	13	122	480	1125	1962	3540	34.7

(a) Fabrication history, conversion variables, and interstitial analyses for data presented in this table were given previously (see Figure A-121 and Tables A-84 and A-85).

(b) Test Conditions

Atmosphere	Argon-7% hydrogen
Sheet Thickness	0.080 inch
Method of Heating	Resistance

TABLE A-92. CREEP AND STRESS-RUPTURE PROPERTIES OF TZM SHEET[a,b](11)

Temp., F	Stress, 1000 psi	Loading Strain, 1000 psi	Time, sec, to Produce Indicated Plastic Creep										Time to Rupture, sec	Elong. in 1.5 In., per cent
			.05%	0.2%	0.5%	1%	2%	4%	5%	6%	8%	10%		
						Series B-1, 0.040 In.-Thick Sheet								
2000	50	0.2	70	480	2010	--	--	--	--	--	--	--	--	4.3
	65	0.25	3.5	28.5	120	390	920	--	1350	--	--	--	1380	6.7
2500	20	0.13	7.0	58	135	205	27	--	360	--	--	--	518	16.7
	20	0.13	4.0	9.8	35	62	110	--	215	--	--	--	400	20
	15	0.05	80	660	1650	2800	--	--	--	--	--	--	--	13.3
3000	6	0.04	20	75	198	400	760	--	1450	--	--	--	--	22.5
	5	0.01	29	125	290	510	830	--	1500	--	--	--	--	27.3
						Series B-3, 0.040-In.-Thick Sheet								
2000	28	0.47	--	2.4	30	147	1821	3660	--	--	--	--	--	18.5
	25	0.60	3.3	62	345	1225	--	--	--	--	--	--	--	17.5
	18	0.12	28	1825	--	--	--	--	--	--	--	--	--	18.0
2500	20	0.67	--	3.0	12	32	105	610	--	1015	1442	1755	--	19.4
	18	0.20	1.2	8.0	33	264	722	1810	--	3070	--	--	--	18.7
	14	0.13	10	98	515	1090	--	--	--	--	--	--	--	21.4
3000	12	0.20	--	1.0	3	10	35	57	--	88	101	132	222	24
	10	0.13	--	1.0	4.8	15	38	83	--	120	152	178	224	25
	8	0.46	3.0	39	105	227	474	312	--	1199	1370	1530	--	24
2500	40	0.2	--	7.5	45	203	396	590	--	--	--	--	594	21
						Series D-1, 0.080-In.-Thick Sheet								
2000	65[c]	0.3	31	480	1740	--	--	--	--	--	--	--	2680	2.0
	50[c]	0.13	42	3600	--	--	--	--	--	--	--	--	--	1.0
	65	0.33	--	1.0	5.2	12	--	--	--	--	--	--	13	5.0
	50	0.2	30	475	2090	3600+	--	--	--	--	--	--	--	6.7

TABLE A-92. (Continued)

Temp., F	Stress, 1000 psi	Loading Strain, 1000 psi	Time, sec, to Produce Indicated Plastic Creep .05%	0.2%	0.5%	1%	2%	4%	5%	6%	8%	10%	Time to Rupture, sec	Elong. in 1.5 In., per cent
						Series D-1, 0.080-In.-Thick Sheet (Continued)								
2500	50	--	--	--	--	--	--	--	--	--	--	--	1.5	6.7
	45	0.2	--	0.4	0.9	1.3	1.4	--	--	--	--	--	3.5	6.7
	45[c]	0.2	16	62	186	350	436	440	--	--	--	--	441	6.0
	30[c]	0.07	15	335	1692	2780	3018	3079	--	--	--	--	3080	6.0
	30	0.17	6	42	268	702	1148	1265	--	1274	--	--	1275	9.3
3000	14[c]	0.9	--	0.3	1.0	1.4	3.6	7	--	14	20	27	38	24.0
	12	0.7	--	--	1.0	2.8	7.4	32	--	65	98	124	168	23.4
	10	0.47	0.4	2.5	7.5	42	145	318	--	437	525	580	666	22.7
	8	0.12	58	301	927	1550	1890	2342	--	2784	3075	3357	--	20.7
	6	0.03	215	1380	3600	--	--	--	--	--	--	--	--	20.7
						Series D-2c, 0.040-In.-Thick Sheet								
2000	73	0.5	--	--	--	--	--	--	--	--	--	--	2.5	5.7
	63	0.3	3.5	41	142	473	1240	1735	--	--	--	--	1737	6.0
	42	0.17	5.0	43	267	828	2016	3156	--	3269	--	--	3270	8.3
2500	35	0.2	1.5	15	65	160	295	364	--	--	--	--	366	6.7
	30	0.2	6.0	110	655	1695	2870	3320	--	3483	--	--	3484	8.7
3000	12	0.8	--	0.4	1.0	2.6	7.9	27	--	49	69	88	125	25.4
	10	0.5	0.2	1.6	5.0	13	70	197	--	324	395	530	687	23.4
	8	0.2	12	87	225	385	848	1745	--	2565	3020	3386	--	24.0
						Series EGA, 0.063-In.-Thick Sheet								
2000	75	0.5	--	0.5	1.4	3.8	5	--	--	--	--	--	7	5.3
2500	50	0.27	--	3.5	12	35	62	70	--	--	--	--	74	7.3
3000	10	0.33	0.3	1.6	4.9	16	47	135	--	285	470	640	--	26.7

TABLE A-92. (Continued)

Temp., F	Stress, 1000 psi	Loading Strain, 1000 psi	Time, sec, to Produce Indicated Plastic Creep .05%	0.2%	0.5%	1%	2%	4%	5%	6%	8%	10%	Time to Rupture, sec	Elong. in 1.5 In., per cent
Series EH-1, 0.088-In.-Thick Sheet														
2000	82	0.30	--	--	0.5	1.1	2.0	--	--	--	--	--	4.0	6.0
	72	0.20	.0	9	45	205	371	--	--	--	--	--	465	6.3
2500	50	0.30	--	0.2	2.0	4.1	6.5	--	--	--	--	--	7.5	7.3
	40	0.23	2.1	20	62	110	136	--	--	--	--	--	142	9.3
3000	12	0.40	--	0.6	2.4	10	31	75	--	199	131	144	162	22.0
	9	0.40	3.0	22	62	145	272	465	--	690	1150	1457	2337	22.0
Series EH-2, 0.040-In.-Thick Sheet														
2000	80	0.33	--	2.0	7.5	20	25	--	--	--	--	--	27	4.3
	75	0.37	3.0	19	71	160	301	--	--	--	--	--	312	4.7
	65	0.23	4.0	44	390	1475	3600+	--	--	--	--	--	--	6.0
2500	45	--	--	--	--	--	--	--	--	--	--	--	2.0	7.0
	40	0.2	4.0	24	105	176	245	--	--	--	--	--	272	6.0
3000	12	0.27	0.2	1.2	3.5	15	50	107	--	147	180	193	199	15.3
	10	0.27	0.3	1.3	4.0	87	195	331	--	435	505	562	596	15.3
	8	0.13	13	65	142	296	640	1310	--	1697	1988	2210	--	24.0
Series EH-3, 0.040-In.-Thick Sheet														
2000	35	1.6	--	1.3	45	248	570	1522	--	1660	1701	1712	1715	15.7
	25	0.3	20	675	3600	--	--	--	--	--	--	--	--	14.0
2500	18	0.23	6.5	52	215	654	1305	2925	--	3600+	--	--	--	17.3
	13	0.07	12	810	2270	3600+	--	--	--	--	--	--	--	17.3
3000	8	0.05	9	67	225	530	915	1365	--	1594	1790	1895	--	21.3
	6	0.04	42	210	552	1365	2076	2925	--	3482	--	--	--	20.6

(a) Fabrication history, conversion variables, and interstitial analyses for data in this table are given previously (see Figure A-121 and Tables A-84 and A-85).

(b) Test Conditions: Atmosphere Argon-7% hydrogen
Method of Heating Resistance

(c) Transverse.

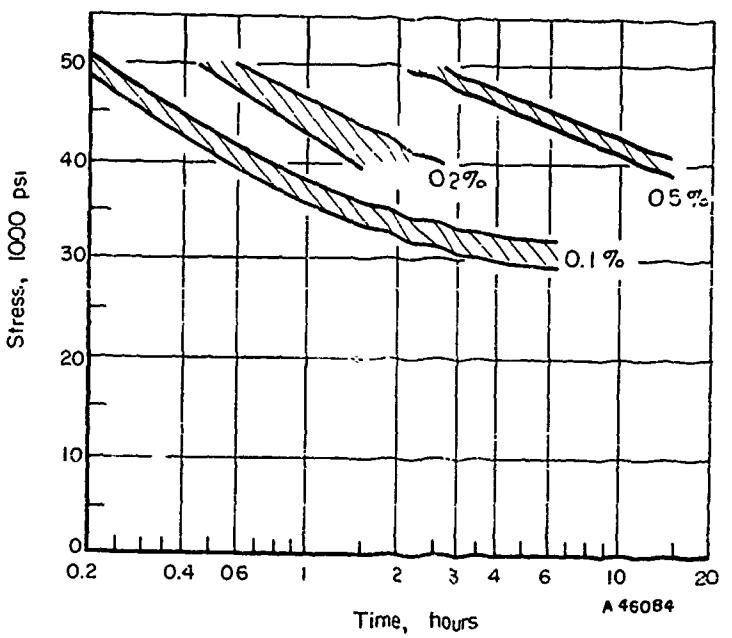


FIGURE A-130. CREEP BEHAVIOR OF DISILICIDE COATED TZM IN AIR AT 2000 F[5]

TABLE A-93. HARDNESS SPECIFICATION FOR WROUGHT AND RECRYSTALLIZED ARC-CAST TZM BARS[a][2]

Diameter, inches	Hardness, DPH[b]	
	Minimum	Maximum
	Wrought	
Over 13/32 to 7/8	260	320
Over 7/8 to 1-1/8	250	310
Over 1-1/8 to 1-7/8	245	300
Over 1-7/8 to 2-7/8	240	290
Over 2-7/8 to 3-1/2	235	285
Over 3-1/2 to 4-1/2	230	280
	Recrystallized	
Over 13/32 to 4-1/2	--	215

(a) Hardness determined at mid-radius of bar
(b) 10-kg load.

TABLE A-94. EFFECT OF TEMPERATURE ON THE HARDNESS OF AS-CAST TZM[5]

Temperature, F	Hardness, DPH[a]
80	172
1600	82
2000	82
2200	80
2400	75
2600	65
2800	55
3000	38

(a) 5-kg load.

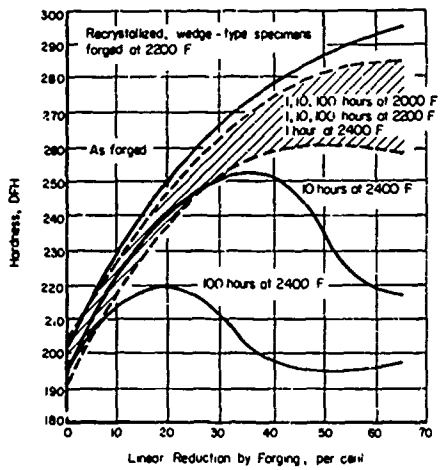


FIGURE A-131. EFFECT OF LINEAR FORGING REDUCTION AND ANNEALING ON THE ROOM-TEMPERATURE HARDNESS OF TZM[5]

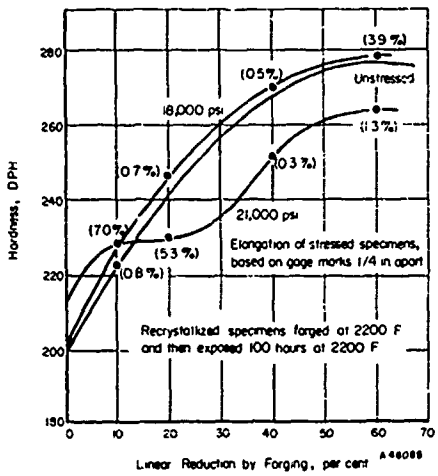


FIGURE A-132. EFFECT OF LINEAR FORGING REDUCTION AND HEATING UNDER IMPOSSED STRESSES ON THE ROOM-TEMPERATURE HARDNESS OF TZM[5]

TABLE A-95. BEND-TEST DATA FOR TZM SHEET (1/16 INCH)[8]

Carbon Content, weight per cent	Condition	Specimen Orientation[a], degrees	Temperature, F, for Indicated Bend Angle		Bend Angle at 75 F, degrees
			10 Degrees	90 Degrees	
0.019	As rolled	0	9	16	140
	Stress relieved	0	-6	-1	140
	Recrystallized	0	91	101	0
	As rolled	90	100	415	6
	Stress relieved	90	88	298	0
	Recrystallized	90	90	172	5
0.054	As rolled	0	-70	-16	138
	Stress relieved	0	51	191	23
	Recrystallized	0	190	192	0
	As rolled	90	-6	390	39
	Stress relieved	90	95	97	2
	Recrystallized	90	205	208	0

(a) Orientation of long dimension with rolling direction.

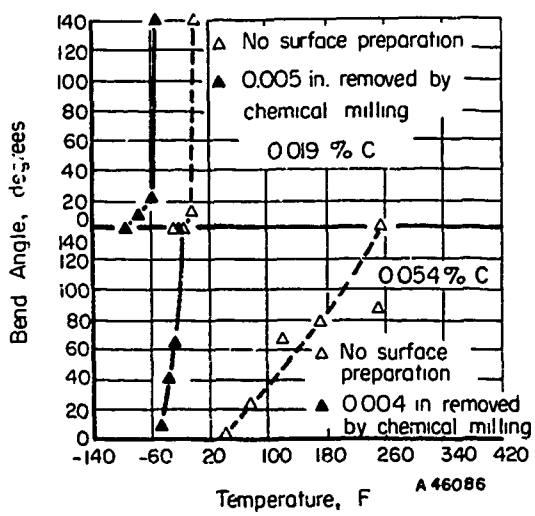


FIGURE A-133. EFFECT OF TEMPERATURE AND AMOUNT OF SURFACE REMOVED BY CHEMICAL MILLING ON THE BEND PROPERTIES OF STRESS-RELIEVED TZM SHEET (1/16 INCH)[8]

Stress relieved 15 minutes at 2000 F. Specimens cut parallel to rolling direction.

4. Metallurgical Properties

a. Fabricability: arc-cast billets can be successfully extruded at temperatures from 2800 to 4000 F using reduction ratios of up to 8:1[12], the most uniform, fine, hot-forged structure is produced in extruded billets forged at 3000 to 3200 F[19], mold-out properties have shown that 0.125-inch material is best produced from extruded ingot and hot-forged sheet bar using rolling temperatures of 2800 F[20]; material can be rolled to thin strip (0.040 inch) at 100 microns of pressure up to 2000 F and exposure times of 15 to 45 minutes without contamination[21]; recommended working temperature after extrusion is illustrated in Figure A-134

b. Transition temperature: Table A-96
Figures A-135 and A-136

c. Weldability: can be welded using fusion or resistance techniques; preheating to 400 to 600 F is recommended; thorough chemical cleaning or electroplating of surface to be joined is essential; properly welded material is room-temperature ductile; welding characteristics (less spatter, sounder weldments) are normally better than either those of unalloyed molybdenum or Mo-0.5Ti – this is thought to be associated with the combined gettering effects of both titanium and zirconium[23]

d. Stress-relief temperature: 1/4 to 1 hour at 2000 to 2300 F for bar and sheet material[5,8]

e. Recrystallization temperature: Tables A-97 through A-100
Figures A-137 through A-142

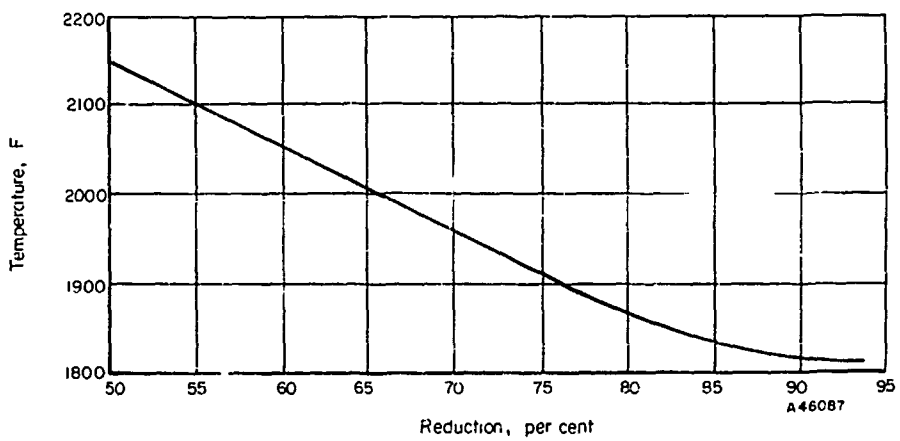


FIGURE A-134. APPROXIMATE RECOMMENDED WORKING TEMPERATURES FOR CORRESPONDING AMOUNTS OF HOT-COLD WORK FOR ARC-CAST TZM[22]

TABLE A-96. BEND- AND TENSILE-TRANSITION-TEMPERATURE RANGES FOR TZM BAR AND SHEET[5]

Form	Condition	Transition-Temperature Range, F
	Bend[a]	
Sheet, 0.040 inch	Stress relieved	<-100
	Recrystallized (50%), 1/2 hour 2500 F	0 to -25
	Recrystallized	-25 to -75
Sheet, 0.015 inch	Stress relieved	<-100
	Recrystallized (50%), 1/2 hour 2500 F	-75 to -100
	Recrystallized	-25 to -75
	Tensile[b]	
Bar, 5/8-inch round	Stress relieved	-2 to -13
		-3 to -12
	Recrystallized	+31 to -45
		+51 to -12
Sheet, 1/16 inch	As rolled	+72 to <-60
	Stress relieved, 2200 F	-42 to -60
	Recrystallized	+29 to -10

(a) 3T bend radius using a ram rate of about 10 inches per minute.
(b) Range corresponding to 20 and 80 per cent maximum elongation.

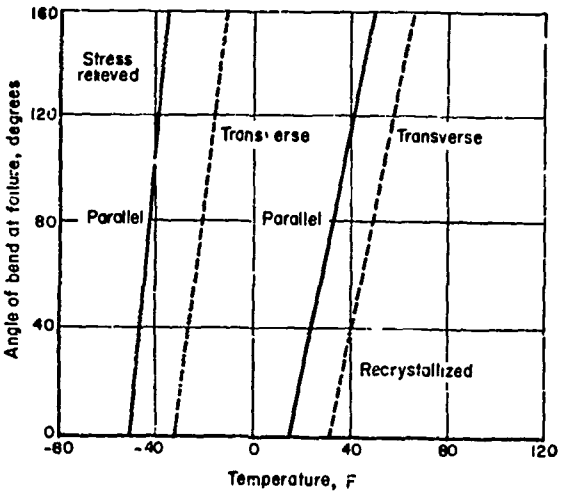


FIGURE A-135. BEND-TRANSITION BEHAVIOR OF STRESS-RELIEVED AND RECRYSTALLIZED TZM SHEET[5]

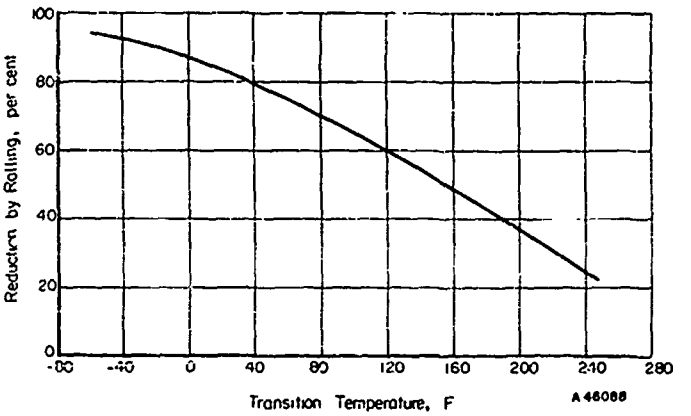


FIGURE A-136. EFFECT OF ROLLING REDUCTION ON THE BEND-TRANSITION TEMPERATURE OF TZM SHEET[11]

Bend radius 1T
Bending rate 1 inch per minute
Minimum bend angle 90 degrees.

TABLE A-97. HARDNESS AND RECRYSTALLIZATION OF FORGED TZM[a][12]

Forging Reduction, per cent	Forged Hardness, DPH	Hardness and Per Cent Recrystallization After 1-Hour Exposure at Indicated Temperature									
		2800 F		3000 F		3200 F		3400 F		3600 F	
		DPH	%	DPH	%	DPH	%	DPH	%	DPH	%
20	238	223	10	203	20	203	40	193	30	165	100
40	243	206	20	206	40	200	60	193	90	173	100
50	248	206	20	214	40	200	60	193	100	176	100
70	243	200	40	220	50	197	70	176	100	193	100

(a) Forged at 1900 F.

TABLE A-98. INFLUENCE OF FORGING TEMPERATURE AND FORGING REDUCTION ON THE RECRYSTALLIZATION BEHAVIOR OF TZM[25]

Forging Temperature, F	Reduction, per cent	Approximate 1-Hour Annealing Temperature for Recrystallization, F	
		Recrystallization Begins	Recrystallization Complete
2200	30	2600	2800
	60	2500	2700
2400	10	--	3000
	30	2600	2800
	60	--	2700
2900	10	2800	3200
	30	2600	3000
	60	--	2700
3400	10	3000	3200
	30	2800	3000
	60	2700	2800

TABLE A-99. EFFECT OF ANNEALING TEMPERATURE ON RECRYSTALLIZATION AND HARDNESS OF TZM SHEET[11]

1-Hour Annealing Temperature, F	Recrystallization, per cent	Hardness, VHN
As received[a]	0	310
2200	0	327
2400	50	232
2500	100	204
2600	100	206
2800	100	205

(a) Stress relieved 1 hour at 2200 F.

TABLE A-100. EFFECT OF EXPOSURE TIME AT 2200 F IN ARGON ON THE MICROSTRUCTURE OF VARIOUS AS-ROLLED AND STRESS-RELIEVED TZM SHEETS[11]

Sheet Thickness, inch	Condition	Reduction After Last Recrystallization, per cent	Microstructure After Exposure at Indicated Times			
			1 Hour	5 Hours	16 Hours	24 Hours
0.080	Stress relieved	65	←	No change	→	
0.080	As rolled	65	←	No change	→	
0.040	Stress relieved	82	←	No change	→	Slight recrystallization
0.040	As rolled	82	←	No change	→	Slight recrystallization
0.120	Stress relieved	20	←	No change	→	
0.120	As rolled	20	←	No change	→	
0.040	Stress relieved	73	←	No change	→	Slight recrystallization
0.080	As rolled	--	No change	Slight recrystallization, still cold-worked structure		
0.120	Stress relieved	47	←	No change	→	
0.080	Stress relieved	65	←	No change	→	
0.040	Stress relieved	82	←	No change	→	Slight recrystallization
0.088	Stress relieved	84	←	No change	→	Slight recrystallization
0.040	Stress relieved	93	←	No change	Very slight recrystallization	Noticeable recrystallization
0.063	Stress relieved	67	←	No change	→	Very slight recrystallization
0.078	Stress relieved	61	←	No change	→	
0.117	Stress relieved	42	←	No change	→	
0.040	Stress relieved	92	←	No change	Very slight recrystallization	Noticeable recrystallization

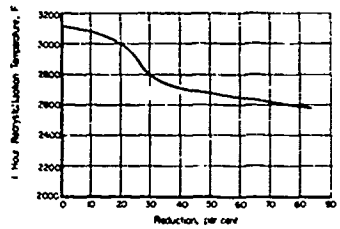


FIGURE A-137. EFFECT OF DEFORMATION ON THE MINIMUM TEMPERATURE FOR COMPLETE RECRYSTALLIZATION OF ARC-CAST TZM[22]

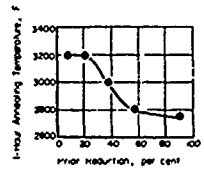


FIGURE A-138. EFFECT OF PRIOR REDUCTION ON THE RECRYSTALLIZATION TEMPERATURE OF ROLLED TZM BAR (5/8-INCH DIAMETER)[26]

Rolled at 2200 F to indicated reduction.

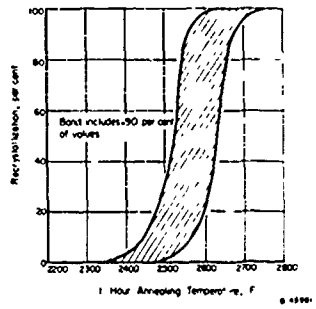
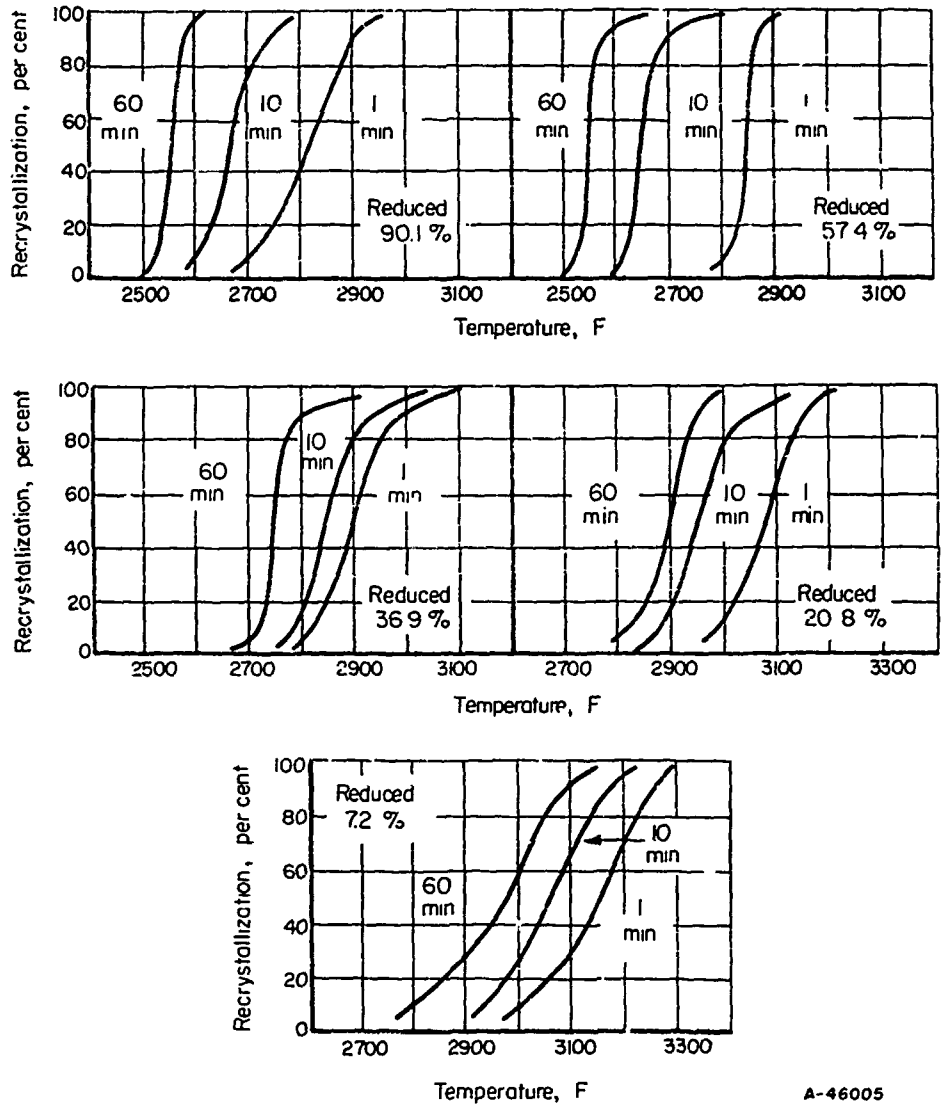


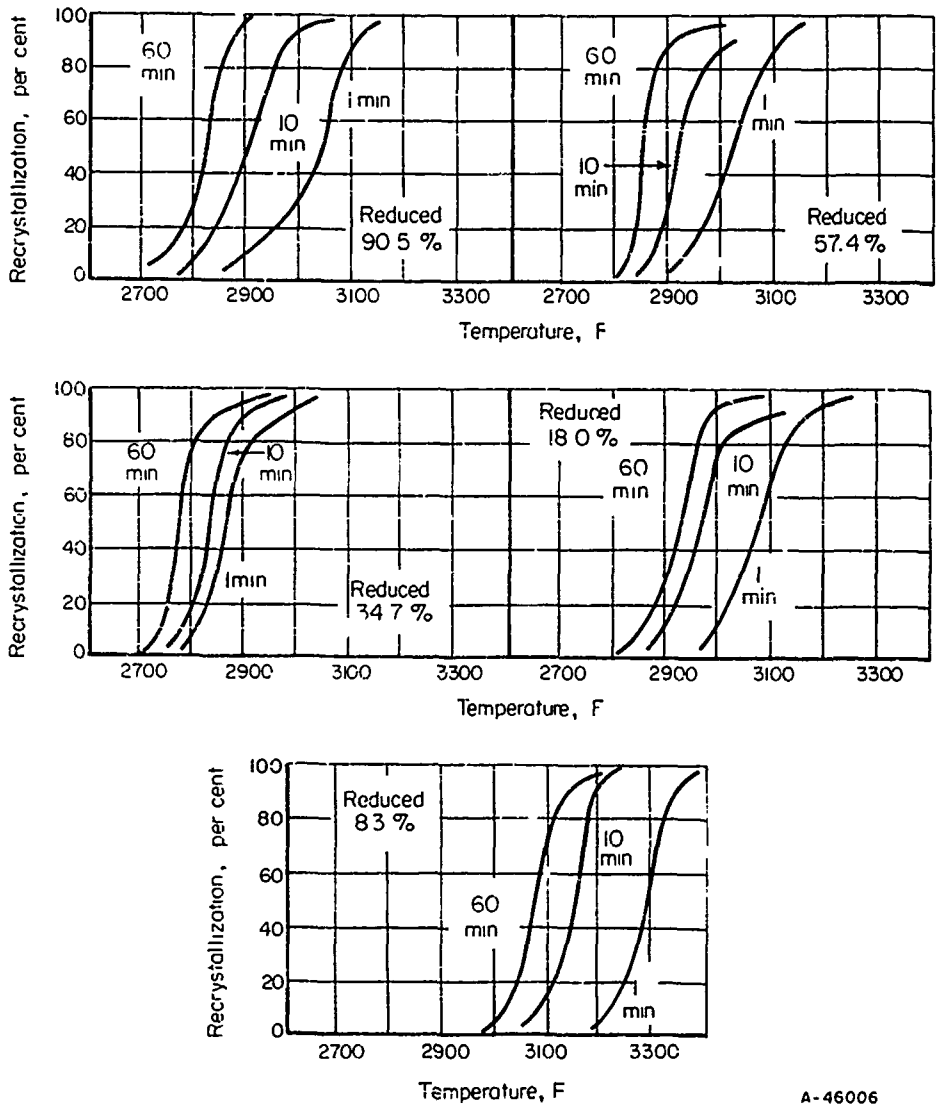
FIGURE A-139. RECRYSTALLIZATION BEHAVIOR OF WROUGHT TZM BARS REDUCED 50 PER CENT OR MORE BY ROLLING OR FORGING BELOW THE RECRYSTALLIZATION TEMPERATURE[5]



a Rolled at 2200 F

FIGURE A-140. RECRYSTALLIZATION BEHAVIOR AS A FUNCTION OF TIME AND TEMPERATURE FOR TZM BARS ROLLED TO INDICATED REDUCTIONS[24]

Analyses 0.49% Ti, 0.067% Zr, and 0.031% C.



b Rolled at 3000 F

FIGURE A-110. (CONTINUED)

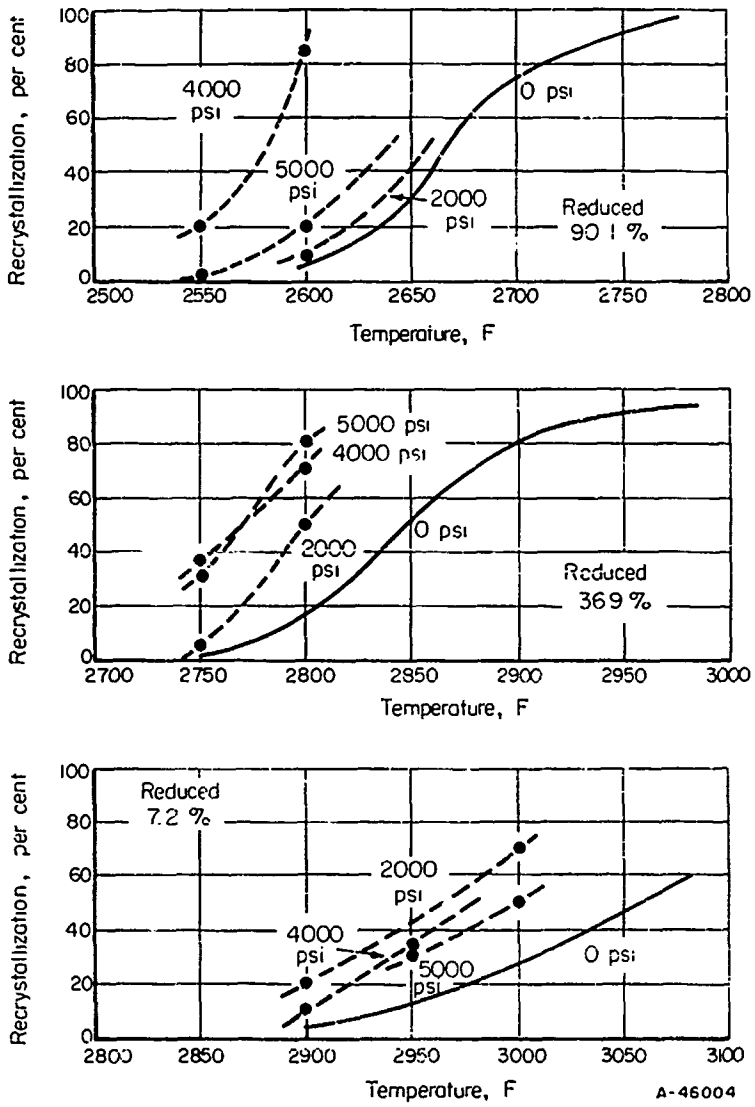


FIGURE A-111. RECRYSTALLIZATION BEHAVIOR AS A FUNCTION OF TEMPERATURE AND EXTERNALLY APPLIED STRESS FOR TZM BARS[24]

Annealed for 10-minute periods.

Subjected to indicated reduction at 2200 F

Analyses 0.40% Ti, 0.057% Zr, and 0.031% C.

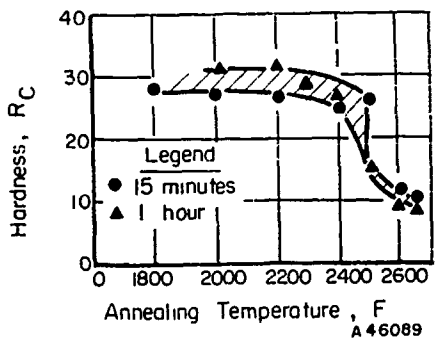


FIGURE A-142. EFFECT OF ANNEALING TEMPERATURE AND TIME ON THE HARDNESS OF TZM SHEET (1/16 INCH)[8]

0.019% carbon.

References

(1) "Specification for Climelt Molybdenum-0.5 Per Cent Titanium-0.08 Per Cent Zirconium (TZM) Forging Billets", Climax Molybdenum Co., Specification Number CMX-FB-TZM-2 (October, 1961).

(2) "Specification for Climelt Molybdenum-0.5 Per Cent Titanium-0.08 Per Cent Zirconium (TZM) Wrought Bars", Climax Molybdenum Co., Specification Number CMX-WB-TZM-1 (October, 1961).

(3) "Specification for Climelt TZM Sheet", Climax Molybdenum Co., Specification Number CMX-S-TZM-1 (June, 1962).

(4) "Molybdenum + 0.5% Titanium + 0.1% Zirconium Sheet", Universal Cyclops Steel Corp., Specification No. MTZS-61-11 (November 28, 1961).

(5) "Developmental Data Climelt TZM", Climax Molybdenum Co. (January, 1962).

(6) Private communication from G. D. McArdle, Climax Molybdenum Co. (1963).

(7) Semchyshen, M., McArdle, G. D., and Barr, R. Q., "Development of Molybdenum-Base Alloys", Climax Molybdenum Co., WADC TR 59-280 (October, 1959).

(8) Semchyshen, M., and Barr, R. Q., "Mechanical Properties of Molybdenum and Molybdenum-Base Alloy Sheet", ASTM STP No. 272 (1959).

(9) Savage, C. H., and Root, D. C., "Determination of Mechanical and Thermophysical Properties of Coated Refractory and Superalloy Thin Sheet", North American Aviation, Inc., Contract No. AF 33(657)-9416, Third Progress Report (April 15, 1963).

(10) Savage, C. H., and Root, D. C., "Determination of Mechanical and Thermophysical Properties of Coated Refractory and Superalloy Thin Sheet", North American Aviation, Inc., Contract No. AF 33(657)-9416, Second Progress Report (January 15, 1963).

(11) Jones, O. Jr., Bennett, A., and Albom, M. J., "Fabrication Techniques and Mechanical Properties at Elevated Temperatures of TZM Alloy Sheet", The Marquardt Corp., ASD-TDR-62-936 (September 14, 1962).

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

(13) Private communication from R. B. Bargainnier, Sylvania Electric Products, Inc. (1963).

(14) Neff, C. W., Frank, R. G., and Luft, L., "Refractory Metals Structural Development Program", McDonnell Aircraft Corp. and General Electric Co., Refractory Alloy and Coating Development, ASD TR 61-392, Vol. II (October, 1961).

(15) Technical Note, Climax Molybdenum Co. (February, 1959).

(16) "Arc-Cast Molybdenum and Its Alloys, Mechanical and Elevated Temperature Properties", Climax Molybdenum Co.

(17) Barr, R. Q., and Semchyshen, M., "Stress-Strain Curves for Wrought Molybdenum and Three Molybdenum-Base Alloys", Climax Molybdenum Co. (December, 1959).

(18) Semchyshen, M., McArdle, G. D., and Barr, R. Q., "Development of High Strengths and High Recrystallization Temperatures in Molybdenum-Base Alloys", Climax Molybdenum Co., WADC TR 48-551 (February, 1959).

(19) Houck, J. A., "Review of Recent Developments – Molybdenum and Molybdenum-Base Alloys", Battelle Memorial Institute, DMIC (March 22, 1963).

(20) Houck, J. A., "Review of Recent Developments – Molybdenum and Molybdenum-Base Alloys", Battelle Memorial Institute, DMIC (June 28, 1963).

(21) Cortes, F. R., "Determination of The Effects of Processing Refractory Metals Under Vacuum", Universal Cyclops Steel Corp., ASD-TDR-62-618 (February, 1963).

(22) "Forging of Vacuum Arc-Cast Molybdenum, Mo + 0.5% Ti and Mo + 0.5% Ti + 0.1% Zr (TZM)", Universal Cyclops Steel Corp., Technical Bulletin No. 2 5.3 (September 25, 1962).

(23) Private communication from F. Nair, Climax Molybdenum Co. (1963).

(24) Semchyshen, M., and Barr, R. Q., "Extrusion and Mechanical Properties of Some Molybdenum- and Tungsten-Base Alloys", Climax Molybdenum Co., ASD TR 61-193 (May, 1961).

(25) Henning, H. J., et al., "A Study of Forging Variables", Battelle Memorial Institute, Interim Reports, Contract No. AF 33(600)-42963 (October, 1961 and January, 1962).

(26) Semchyshen, M., Barr, R. Q., and McArdle, G. D., "Effect of Thermal-Mechanical Variables on the Properties of Molybdenum Alloys, Climax Molybdenum Co., WADD TR 60-451 (1960).

Mo-1.2Ti-0.25Zr-0.15C

1. Identification of Material

   a. Designation: TZC

   b. Chemical composition: Mo-1.2Ti-0.25Zr-0.15C

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

2. Physical Properties

   a. Density: 0.363 lb/in.^{3} (calculated)

3. Mechanical Properties

   a. Tensile Properties at Room Temperature

      Ultimate tensile strength: Table A-101

      Tensile yield strength: Table A-101

      Elongation: Table A-101

      Reduction in area: Table A-101

   b. Effect of Temperature on Tensile Properties

      Ultimate tensile strength: Tables A-102 through A-104
      Figures A-143 through A-146

      Tensile yield strength: Table A-102
      Figures A-143 and A-144

      Elongation: Table A-102
      Figures A-143 through A-145

      Reduction in area: Table A-102

   c. Creep and Stress-Rupture Properties

      Tables A-105 through A-108
      Figure A-147

   d. Other Selected Mechanical Properties

      Bend ductility: Figures A-148 through A-150

TABLE A-101. ROOM-TEMPERATURE TENSILE PROPERTIES OF TZC BAR AND SHEET

Condition	Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation, per cent	Reduction in Area, per cent
	Bar[a][1]			
Stress relieved, 1 hour 2200 F	143.6	104.8[b]	22	36.0
Recrystallized, 1 hour 3400 F	84.9	52.3[c]	8	8.6
	Sheet (0.070 Inch)[d][2]			
Stress relieved, 288 VHN	112.9 (T)	104.6 (T)	22 (T)	34 (T)
	Sheet (0.045 Inch)[e][3]			
Stress relieved	128.9 (L)	124.7 (L)	0 (L)	--
Stress relieved	99.3 (T)	--	0 (T)	--
CR, Stress relieved	154.8 (L)	135.0 (L)	0.1 (L)	--
CR, Stress relieved	39.4 (T)	--	0	--

(a) Test rate 0.0005 inch per inch per minute through yielding, then 0.01 inch per inch per minute to fracture. Analyses 1.23% Ti, 0.27% Zr, and 0.14% C.

(b) 0.1 per cent offset.

(c) Drop in load yield strength.

(d) Analyses 1.12% Ti, 0.13% Zr, and 0.131% C.

(e) Stress relieved 1 hour at 2200 F. Analyses 1.35% Ti, 0.15% Zr, and 0.13% C.

TABLE A-102. TENSILE PROPERTIES OF TZC BAR AND SHEET AT 1800 TO 2400 F

Condition	Temperature, F	Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation, per cent	Reduction in Area, per cent
		Bar[a][1]			
Stress relieved, 1 hour 2200 F	1800	91.9	64.6[b]	17.5	77.8
	2400	63.6	41.5[b]	26	86.9
Recrystallized, 1 hour 3400 F	1800	67.4	17.7[b]	27.5	71.3
	2400	57.1	17.3[b]	36	77.8
		Sheet (0.070 Inch)[c][2]			
Stress relieved	1800	65.0	55.0	8.5	--
Stress relieved	2000	56.2 (L)	50.4 (L)	10 (L)	
Stress relieved	2000	61.1 (T)	--	6 (T)	--
Stress relieved	2200	49.0 (L)	41.0 (L)	11 (L)	--
Stress relieved	2200	53.4 (T)	42.5 (T)	8 (T)	--
		Sheet (0.045 Inch)[d][3]			
Stress relieved	2000	102.1 (L)	91.5 (L)	14.5 (L)	--
Stress relieved	2000	110.5 (T)	96.0 (T)	2.8 (T)	--
CR, Stress relieved	2000	98.0 (L)	90.5 (L)	10.2 (L)	--
CR, Stress relieved	2000	109.9 (T)	93.0 (T)	8.3 (T)	--
Stress relieved	2200	62.8	52.4	5.8	--
CR, Stress relieved	2200	74.9 (L)	60.9 (L)	4.8 (L)	--
CR, Stress relieved	2200	75.1 (T)	49.2 (T)	10.8 (T)	--

(a) Test rate 0.0005 inch per inch per minute through yielding, then 0.01 inch per inch per minute to fracture. Analyses 1.23% Ti, 0.27% Zr, and 0.14% C.

(b) 0.1 per cent offset.

(c) Analyses 1.12% Ti, 0.13% Zr, and 0.131% C.

(d) Stress relieved 1 hour at 2200 F. Analyses 1.35% Ti, 0.15% Zr, and 0.13% C.

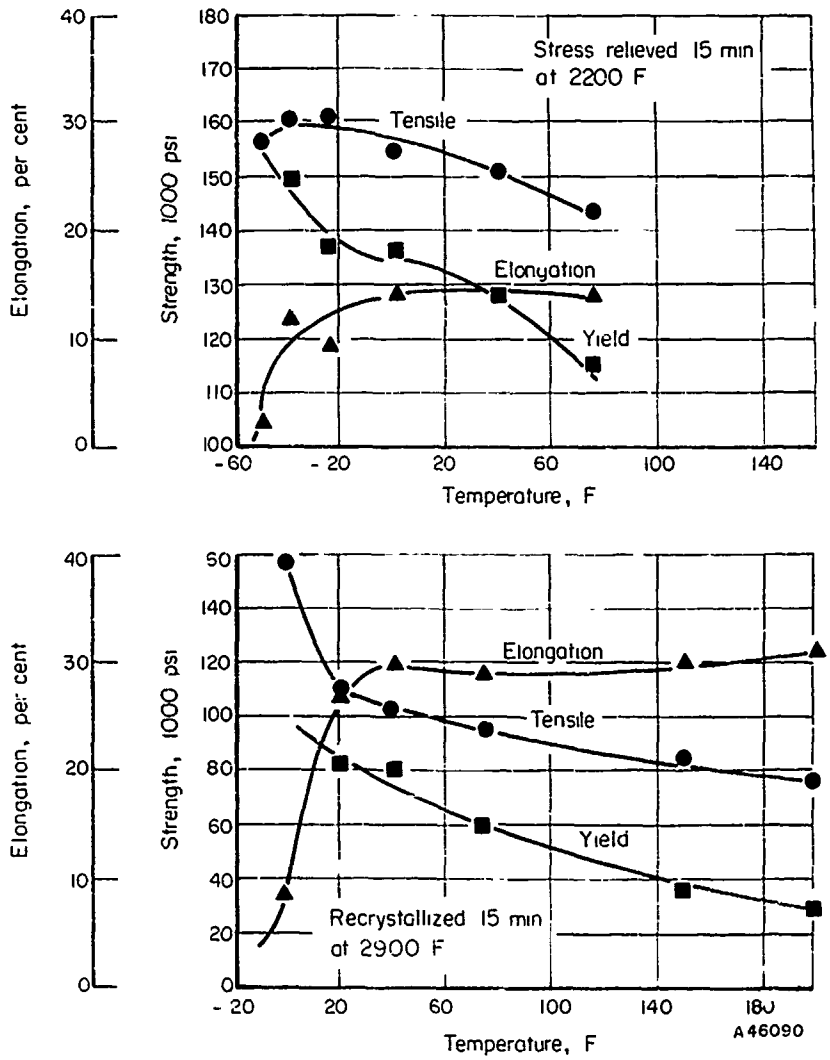
TABLE A-103. EFFECT OF COMPOSITION, STRUCTURAL CONDITION, AND TEMPERATURE ON THE TENSILE STRENGTH OF CLIMAX ARC-CAST TZC[4]

Composition, weight per cent			Structural Condition	Rolled Size,	Tensile Strength, 1000 psi, at Indicated Temperature					
Ti	Zr	C	Prior to Final Rolling	inch	RT	1800 F	2200 F	2400 F	3000 F	3500 F
1.25	0.20	0.054	Recrystallized	1/2 round	149.8	95.4	--	56.[illegible]	13.7	--
1.25	0.32	0.058	Recrystallized	Ditto	--	--	71.2	--	13.8	--
1.25	0.32	0.058	Soln. treated	"	--	--	94.9	--	30.2	--
1.25	0.32	0.058	Soln. treated and aged	"	--	--	96.2	--	17.5	--
1.23	0.13	0.097	Recrystallized	"	147.0	98.9	--	58.0	13.4	--
1.30	0.29	0.12	Recrystallized	"	--	--	76.1	--	13.7	--
1.30	0.29	0.12	Soln. treated	"	--		--	-	15.6	--
1.30	0.29	0.12	Soln. treated and aged	"	--	--	89.3	--	--	--
1.24	0.31	0.13	Recrystallized	5/8 round	-	66.1	--	51.4	--	--
1.29	0.15	0.15	Ditto	0.012 sheet	125.0	--	--	49.2	10.4	--
1.29	0.15	0.13		0.020 sheet	129.4	--	--	48.6	10.6	--
1.23	0.27	0.14	"	1/2 round	143.6	91.9	--	63.6	12.7	6.5
1.17	0.27	0.15	"	0.050 sheet	156.4	--	--	51.8	--	--
1.45	0.31	0.20	Soln. treated and aged	1/2 round	--	--	--	--	24.9	--
1.22	0.31	0.23	Recrystallized	5/8 round	125.1	76.7	--	58.2	--	--
1.27	0.29	0.30	Recrystallized	1/2 round	120.6	91.2	--	60.8	--	--

TABLE A-104. EFFECT OF COMPOSITION AND TEMPERATURE ON THE TENSILE STRENGTH OF CLIMAX ARC-CAST TZC[a][4]

Composition, weight per cent			Rolled Size,	Tensile Strength, 1000 psi, at Indicated Temperature					
Ti	Zr	C	inch	RT	1800 F	2200 F	2400 F	3000 F	3500 F
1.14	0.32	0.014	1/2 round	--	40.7	--	--	--	--
1.25	0.20	0.054	Ditto	92.1	62.3	--	29.1	13.4	--
1.25	0.20	0.054	"	--	--	--	--	24.5[b]	--
1.25	0.32	0.058	"	--	--	33.0	--	13.6	--
1.25	0.32	0.058	"	--	--	44.0[c]	--	24.2[c]	--
1.23	0.13	0.097	"	64.3	62.9	--	30.9	14.2	--
1.23	0.13	0.097	"	--	--	--	--	16.3[b]	--
1.30	0.29	0.12	"	--	--	36.4	--	13.9	--
1.30	0.29	0.12	"	--	--	56.6[c]	--	31.1[c]	--
1.24	0.31	0.13	5/8 round	--	65.6	--	63.5	--	--
1.29	0.15	0.13	0.012 sheet	65.4	--	--	51.2	13.2	--
1.29	0.15	0.13	0.020 sheet	76.0	--	--	53.4	16.3	--
1.23	0.27	0.14	1/2 round	84.9	67.4	--	57.1	18.5	10.1
1.17	0.27	0.15	0.050 sheet	99.6	--	--	31.4	11.5	--
1.17	0.27	0.15	0.050 sheet	--	--	--	--	19.2[b]	--
1.22	0.31	0.23	5/8 round	79.4	66.8	--	67.5	--	--
1.27	0.29	0.30	1/2 round	87.0	61.4	--	46.0	--	--

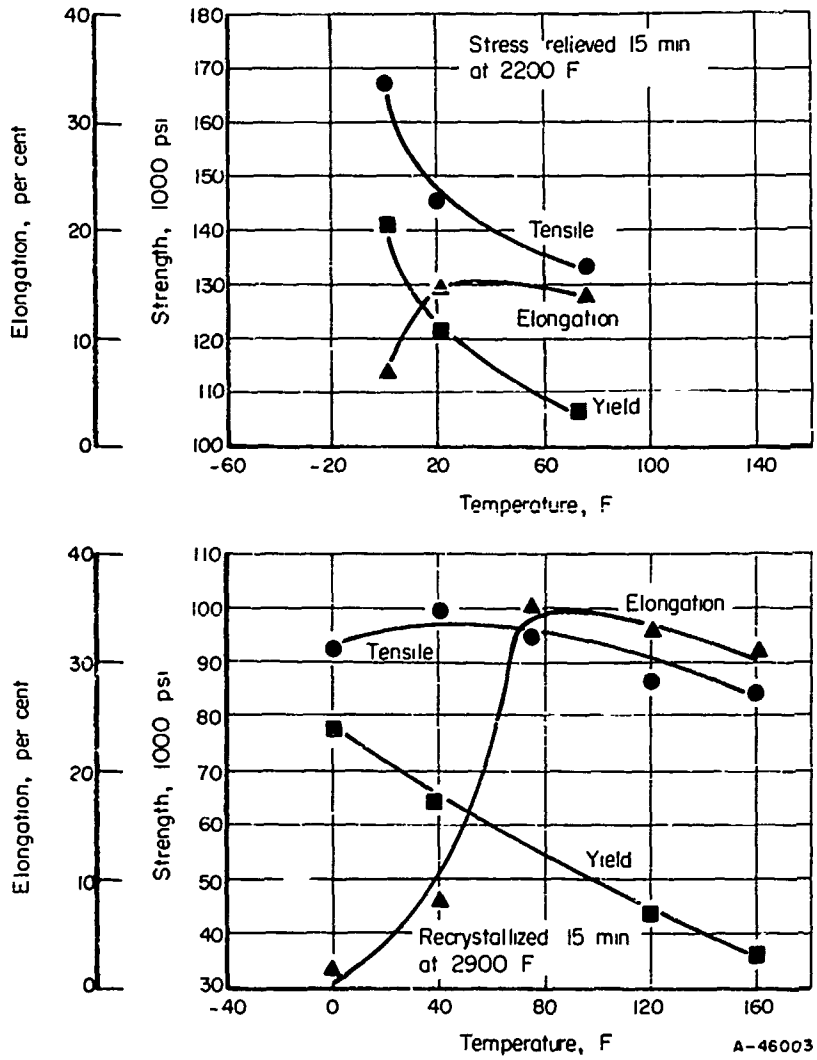
(a) Recrystallized prior to final rolling.
(b) Solution treated after rolling.
(c) Solution treated and aged after rolling.



Sheet rolled in air with a relatively low finishing temperature.

Heat 4053-L, analyses 1.17% Ti, 0.27% Zr, and 0.15% C.

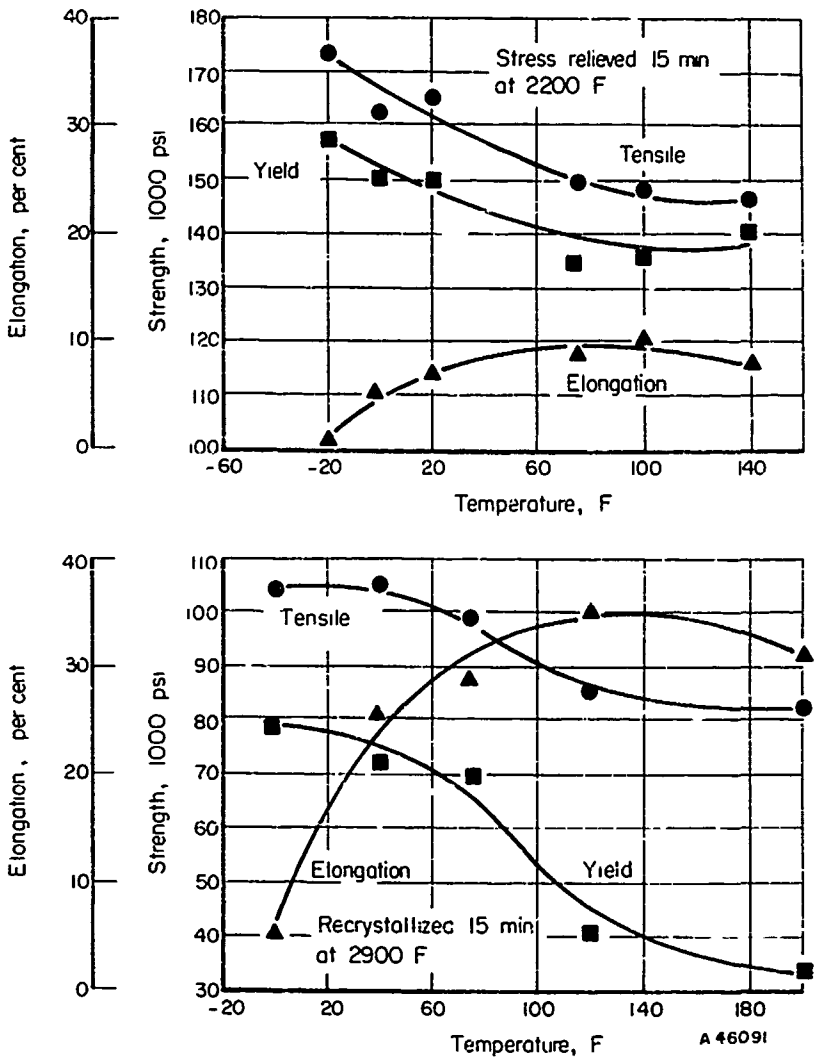
FIGURE A-113. LOW-TEMPERATURE TENSILE PROPERTIES OF LONGITUDINAL STRESS-RELIEVED AND RECRYSTALLIZED TZC SHEET (0.050 INCH)[5]



Sheet rolled in air with a relatively high finishing temperature.

Heat 4053-H, analyses 1.17% Ti, 0.27% Zr, and 0.15% C.

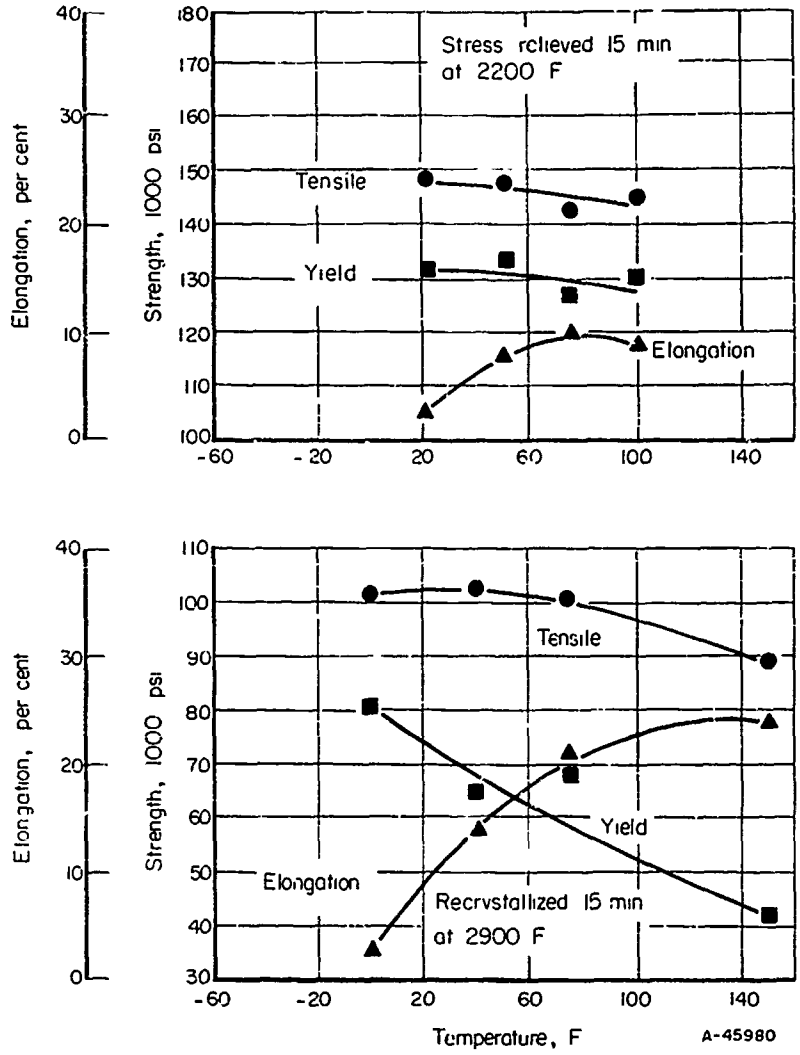
FIGURE A-143. (CONTINUED)



Sheet rolled in air with a relatively low finishing temperature.

Heat 4053-L, analyses 1.17% Ti, 0.27% Zr, and 0.15% C.

FIGURE A-144. LOW-TEMPERATURE TENSILE PROPERTIES OF TRANSVERSE STRESS-RELIEVED AND RECRYSTALLIZED TZC SHEET (0.050 INCH)[5]



Sheet rolled in air with a relatively high finishing temperature.

Heat 1053-H, analyses 1.17% Ti, 0.27% Zr, and 0.15% C.

FIGURE A-144. (CONTINUED)

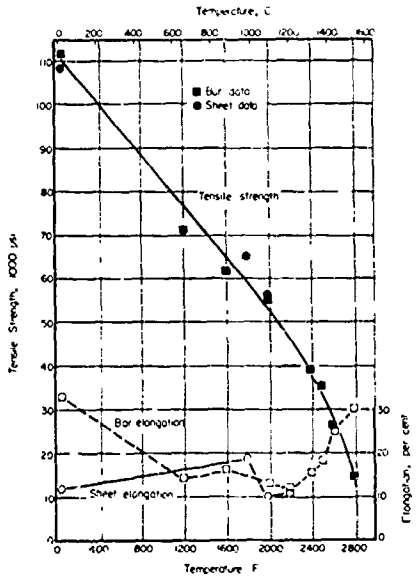


FIGURE A-145. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF STRESS-RELIEVED TZC BAR AND SHEET[2]

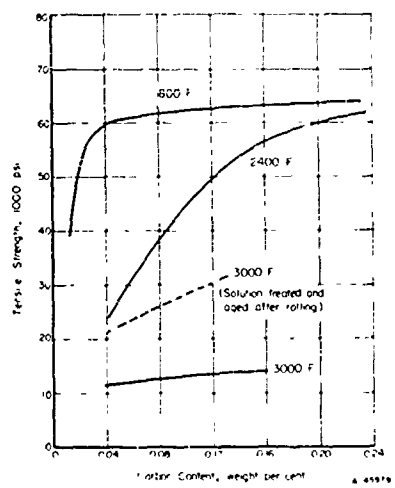


FIGURE A-146. EFFECT OF CARBON CONTENT AND TEMPERATURE ON THE TENSILE STRENGTH OF CLIMAX RECRYSTALLIZED ARC-CAST TZC BAR STOCK[4]

TABLE A-105. CREEP AND STRESS-RUPTURE PROPERTIES OF TZC BAR AT 1800 AND 2400 F[a][1]

Condition	Temperature, F	Stress, 1000 psi	Minimum Creep Rate, per cent/hour	Rupture Time, hours	Elongation, per cent	Reduction in Area, per cent
Stress relieved, 1 hour 2200 F	1800	75.0	1.12	2.2	20	75.5
		69.0	--	45.4	20	79.8
	2400	35.0	1.39	3.3	34	88.0
Recrystallized, 1 hour 3400 F	1800	55.0	--	170.5[b]	9	7.9
		53.0	--	92.7[b]	8	6.3
	2400	32.0	0.023	55.3	38	83.0
		27.0	--	151.6[b]	1	0.4

(a) Analyses 1.23% Ti, 0.27% Zr, and 0.14% C.
(b) Test discontinued.

TABLE A-106. 1- AND 10-HOUR RUPTURE STRENGTHS OF TZC BAR AT 1800 AND 2400 F[a][1]

Condition	Temperature, F	Stress, 1000 psi, to Produce Rupture	
		1 Hour	10 Hours
Stress relieved, 1 hour 2200 F	1800	76.7	72.0
	2400	42.0	29.0
Recrystallized, 1 hour 3400 F	1800	65.0	60.0
	2400	50.0	38.5

(a) Analyses 1.23% Ti, 0.27% Zr, and 0.14% C.

TABLE A-107. STRESS-RUPTURE PROPERTIES OF STRESS-RELIEVED TZC AT 2200 AND 2500 F[2]

Temperature, F	Stress, 1000 psi	Rupture Time, hours	Elongation, per cent	Reduction in Area, per cent
		1.2% Ti, 0.13% Zr, and 0.13% C		
2200	32.0	30.3	24.0	73.0
	30.0	40.6	27.0	82.0
	27.0	78.2	27.5	83.0
	25.0	179.0	13.0	46.0
	20.0	322.0	20.0	79.0
2500	20.0	10.8	24.0	77.0
	17.0	67.0	23.0	70.0
		1.25% Ti, 0.15% Zr, and 0.15% C		
2200	20.0	1000+	5.0	--
	25.0	231.0	12.8	--
	30.0	69.0	18.8	--
	35.0	6.8	13.7	--
2500	17.0	108.8	20.0	--

TABLE A-108. EFFECT OF COMPOSITION AND TEMPERATURE ON THE STRESS-RUPTURE PROPERTIES OF CLIMAX ARC-CAST TZC[a][4]

Composition, weight per cent			Rolled Size, inch	Stress, 1000 psi, to Produce Rupture in 10 Hours at Indicated Temperature, F					
				Stress Relieved		Recrystallized			
Ti	Zr	C		1800	2400	1800	2200	2400	3000
1.30	0.29	0.12	1/2 round	--	--	--	50.0[b]	--	11.5[b]
1.24	0.31	0.13	5/8 round	60.0	37.0	52.0	--	39.5	--
1.23	0.27	0.15	1/2 round	72.0	29.0	60.0	--	38.5	--
1.17	0.27	0.14	0.050 sheet	--	21.0	--	--	18.5	6.9
1.22	0.31	0.23	5/8 round	63.0	48.0	>58.0	--	46.0	--
1.27	0.29	0.30	1/2 round	67.0	41.5	56.0	--	32.0	--
Elongation, per cent				8-20	13-34	10-28	12-18	7-53	10-92

(a) Recrystallized prior to final rolling.
(b) Solution treated and aged after rolling.

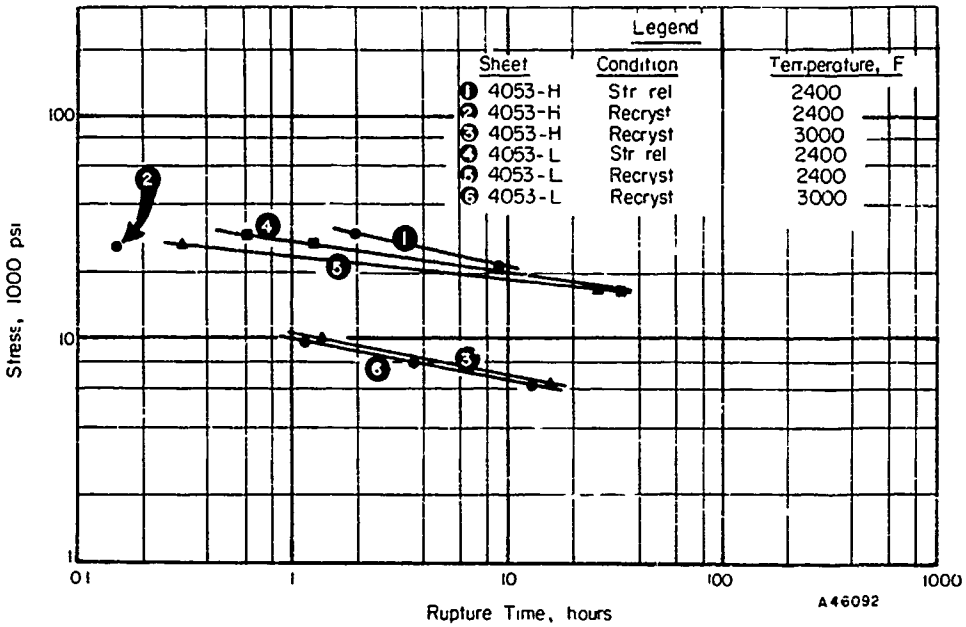


FIGURE A-147. STRESS-RUPTURE BEHAVIOR OF STRESS-RELIEVED AND RECRYSTALLIZED TZC SHEET AT 2400 AND 3000 F[5]

4053-L sheet rolled in air with a relatively low finishing temperature.

4053-H sheet rolled in air with a relatively high finishing temperature.

Analyses 1.17% Ti, 0.27% Zr, and 0.15% C.

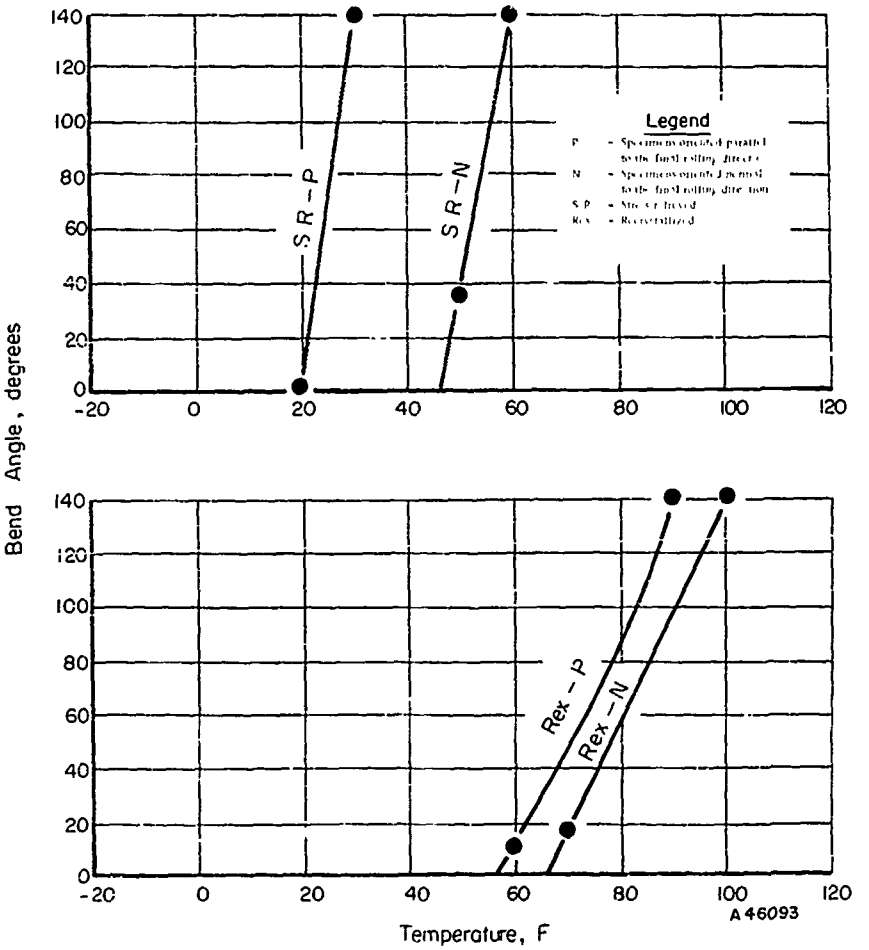


FIGURE A-148. BEND-DUCTILITY BEHAVIOR OF STRESS-RELIEVED AND RECRYSTALLIZED TZC SHEET (0.051 INCH)[5]

Sheet rolled in air with a relatively low finishing temperature.

Heat 4053-L, analyses 1.17% Ti, 0.27% Zr, and 0.15% C.

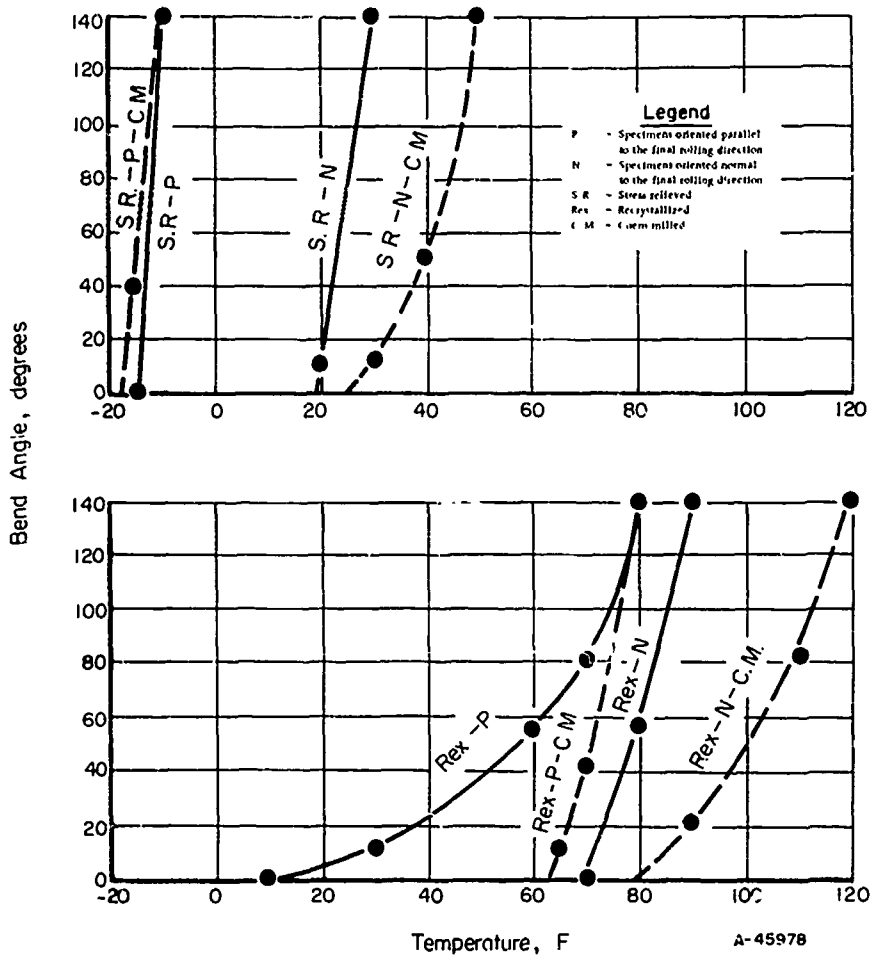


FIGURE A-149. EFFECT OF TEMPERATURE, THERMAL TREATMENT, AND SURFACE CONDITION ON THE BEND DUCTILITY OF TZC SHEET (0.052 INCH)[5]

Sheet rolled in air with a relatively high finishing temperature.

Specimens chemically milled to 0.049 inch.

Heat 4053-H, analyses 1.17% Ti, 0.27% Zr, and 0.15% C.

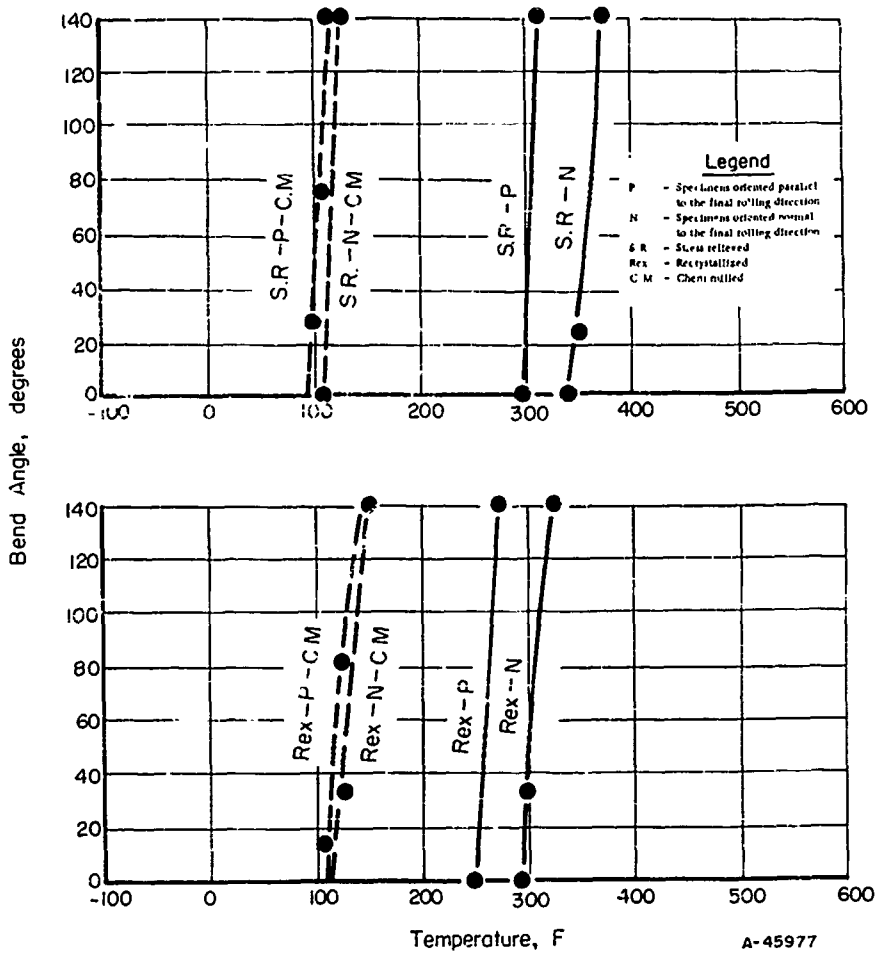


FIGURE A-150. EFFECT OF TEMPERATURE, THERMAL TREATMENT, AND SURFACE CONDITION ON THE BEND DUCTILITY OF TZC SHEET (0.054 TO 0.058 INCH)[5]

Rolled in InFab facility.

Specimens chemically milled 0.004 inch.

Heat 4053-I. analyses 1.17% Ti, 0.27% Zr, and 0.15% C.

4. Metallurgical Properties

a. Fabricability: the following schedule has been successfully used to convert ingot to sheet: (1) extrude at 2850 F; (2) forge extruded sheet bar at 3000 F, (3) breakdown rolling of forged bar at 2500 to 2700 F; (4) roll to plate sizes at 2400 to 2600 F; and (5) sheet rolling at 2400 to 2600 F[3]

b. Transition temperature: Tables A-109 and A-110

c. Stress-relief temperature: 1 hour at 2200 F for bar material[1], 1/4 hour at 2200 F for sheet (0.050 inch) material[5]

d. Recrystallization temperature: 1 hour at 3400 F for bar material[1]; 1/4 hour at 2900 to 3000 F for sheet (0.050 inch) material[5]

Figures A-151 and A-152

TABLE A-109. BEND-TRANSITION TEMPERATURES FOR CLIMAX ARC-CAST TZC SHEET[4]

Composition, weight per cent			Final Rolling Conditions	Sheet Thickness, inch	Minimum Temperature, F, for 140-Degree Bend[a]							
					Stress Relieved				Recrystallized			
					Parallel Rolling Dir.		Perpendicular Rolling Dir.		Parallel Rolling Dir.		Perpendicular Rolling Dir.	
Ti	Zr	C			Rolled Surface	Chem-Milled Surface	Rolled Surface	Chem-Milled Surface	Rolled Surface	Chem-Milled Surface	Rolled Surface	Chem-Milled Surface
1.29	0.15	0.13	2000 F in air	0.012	+10	--	-40	--	+70	--	+50	--
1.29	0.15	0.13	Ditto	0.020	-10	--	+70	--	+130	--	+160	--
1.17	0.27	0.15	2200 F in air	0.051	+30	--	+60	--	+90	--	+100	--
1.17	[illegible]	[illegible]	2500 F in air	0.052	-10	-10	+30	+50	+80	+80	+90	+120
1.17	0.27	0.15	2400 F in Inhab	0.055	+315	+115	+375	+125	+275	+150	+325	+150

(a) 2T radius, 10 inches per minute.

TABLE A-110. TENSILE-TRANSITION TEMPERATURES FOR CLIMAX ARC CAST TZC SHEET[4]

Composition, weight per cent			Final Rolling Conditions	Sheet Thickness, inch	Minimum Temperature, F, for 10 Per Cent Elongation							
					Stress Relieved				Recrystallized			
					Parallel Rolling Dir.		Perpendicular Rolling Dir.		Parallel Rolling Dir.		Perpendicular Rolling Dir.	
Ti	Zr	C			Rolled Surface	Chem-Milled Surface	Rolled Surface	Chem-Milled Surface	Rolled Surface	Chem-Milled Surface	Rolled Surface	Chem-Milled Surface
1.17	0.27	0.15	2200 F in air	0.051	-36	--	+70	--	+2	--	+8	--
1.17	0.27	0.15	2500 F in air	0.052	+6	<-20	+70	+45	+40	<+10	+24	+10

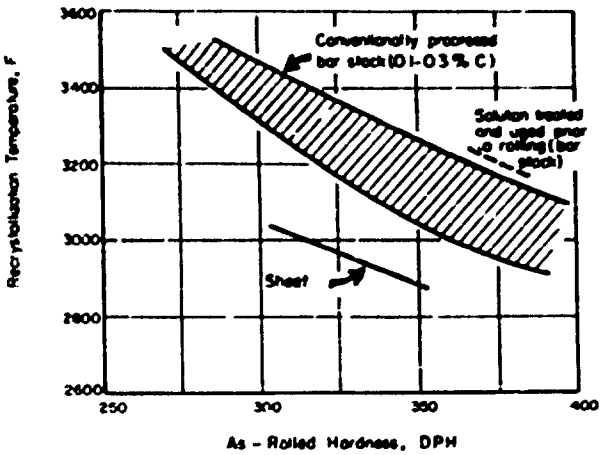


FIGURE A-151. RECRYSTALLIZATION BEHAVIOR OF CLIMAX ARC-CAST TZC BAR AND SHEET[4]

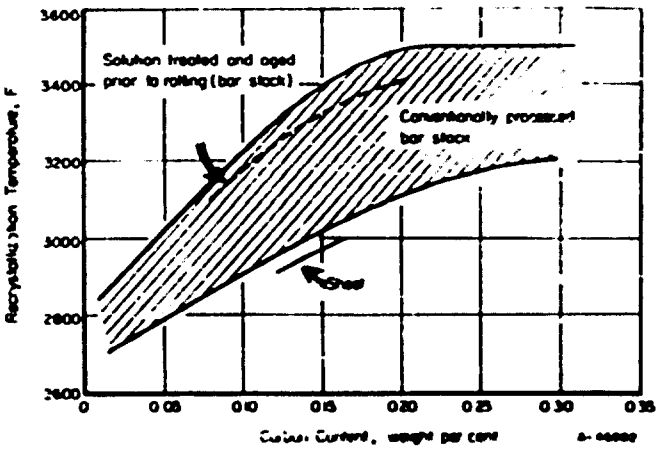


FIGURE A-152. EFFECT OF CARBON CONTENT ON THE RECRYSTALLIZATION BEHAVIOR OF CLIMAX ARC-CAST TZC BAR AND SHEET[4]

References

1. Semchyshen, M., and Barr, R. Q., "Extrusion and Mechanical Properties of Some Molybdenum- and Tungsten-Base Alloys", Climax Molybdenum Company, ASD TR 61-193 (May, 1961).

2. Miketta, D. N., "Additional Tensile and Rupture Properties of TZC Molybdenum Alloy-1959", General Electric Co. (October, 1959).

3. Redden, T. R., "Molybdenum Alloy Sheet Studies During 1957", General Electric Co. (February 28, 1959).

4. Private communication from G. D. McArdle, Climax Molybdenum Co. (1963).

5. McArdle, G. D., Barr, R. Q., and Semchyshen, M., "Investigation of Molybdenum- and Tungsten-Base Alloy Sheet Materials", Climax Molybdenum Co., Contract No. NOw 61-0581-d, Final Report (January 15, 1963).

Mo-25W-0.1Zr-0.03C

1. Identification of Material

   a. Designation: WZM (Climax)

   b. Chemical composition: Mo-25W-0.1Zr-0.03C

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

2. Physical Properties

   a. Melting point: ~5050F (estimated to be about the same as that for Mo-25W)[1]

   b. Density: 0.418 lb/in^3 (calculated)

3. Mechanical Properties

   a. Tensile Properties at Room Temperature

      Ultimate tensile strength: Table A-111

      Tensile yield strength: Table A-111

      Elongation: Table A-111

      Reduction in area: Table A-111

   b. Effect of Temperature on Tensile Properties

      Ultimate tensile strength: Table A-112
      Figures A-153 and A-154

      Tensile yield strength: Table A-112
      Figures A-153 and A-154

      Elongation: Table A-112
      Figures A-153 and A-154

      Reduction in area: Table A-112

c. c. Creep and Stress-Rupture Properties

      Tables A-113 and A-114
      Figure A-155

   d. Other Selected Mechanical Properties

      a. Bend ductility: Figures A-156 through A-158

TABLE A-111. ROOM-TEMPERATURE TENSILE PROPERTIES OF WZM BAR

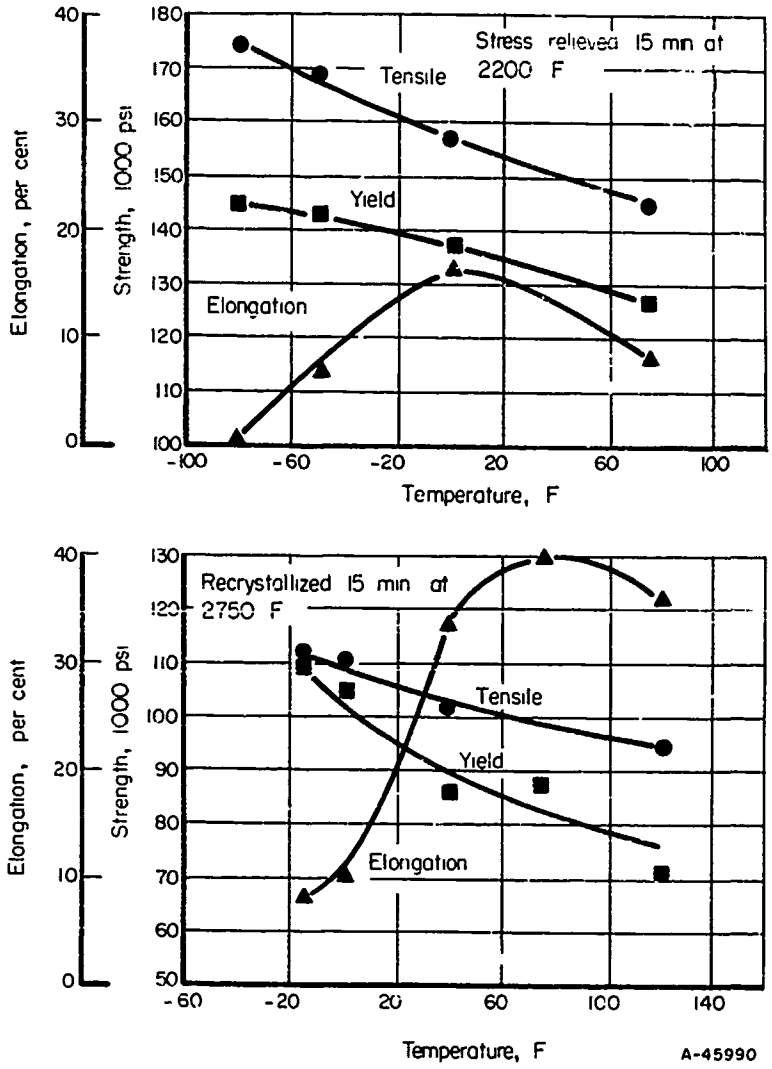
Condition	Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation, per cent	Reduction in Area, per cent
		Reference 2[a]		
Stress relieved, 1 hour 2000 F	145.9	126.5[b]	32	62.5
Recrystallized, 1 hour 2600 F	95.8	89.2[c]	27	23.2
		Reference 3[d]		
Stress relieved	141.3	137.1	0	0
Recrystallized	105.3	79.3	32	25

(a) Test rate 0.005 inch per inch per minute through yielding, then 0.01 inch per inch per minute to fracture. Analyses 26.4% W, 0.106% Zr, and 0.033% C.
(b) 0.1 per cent offset.
(c) Drop in load yield strength.
(d) 1/2-inch stock. Analyses 25.1% W, 0.11% Zr, and 0.051% C.

TABLE A-112. TENSILE PROPERTIES OF WZM BAR AT 1800 AND 2400 F

Condition	Temperature, F	Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation, per cent	Reduction in Area, per cent
		Reference 2[a]			
Stress relieved, 1 hour 2000 F	1800	99.4	31.1[b]	18	75.9
	2400	7[illegible].5	--	22	86.9
Recrystallized, 1 hour 2600 F	1800	45.3	--	39	87.0
	2400	26.9	16.4[b]	59	93.0
		Reference 3[c]			
Stress relieved	1800	98.3	89.6	18	66
Recrystallized	1800	42.8	22.9	46	91
Stress relieved	2400	73.5	--	--	80
Recrystallized	2400	28.5	16.5	58	89.4

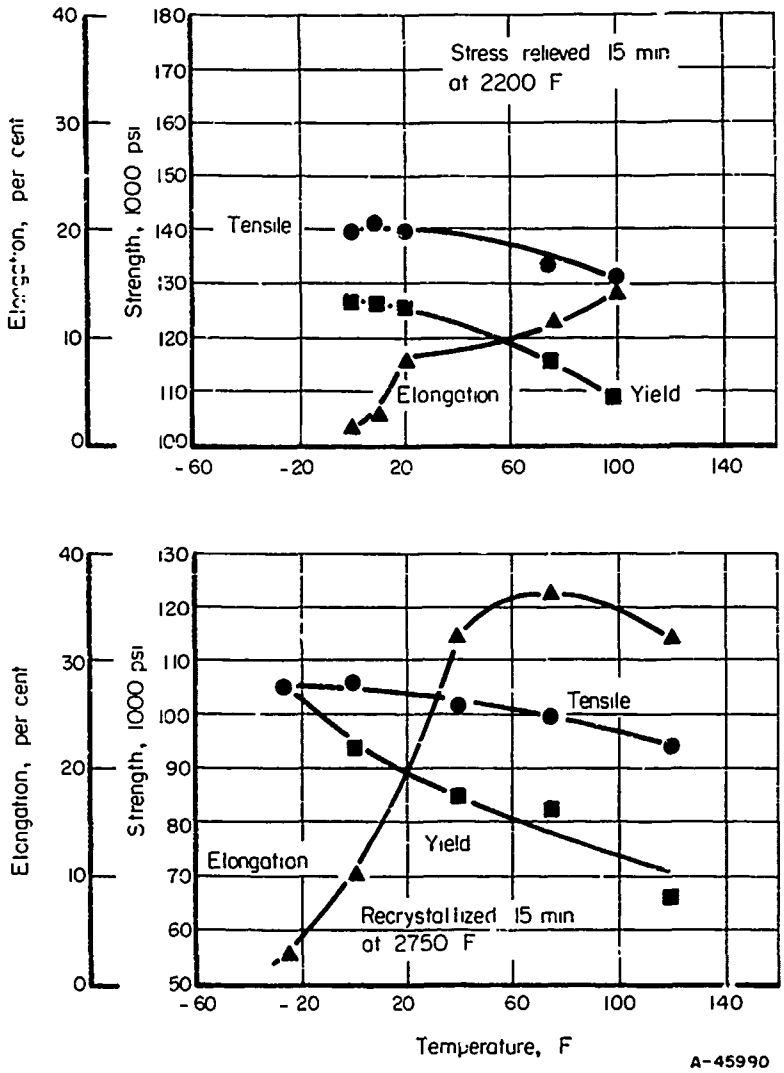
(a) Test rate 0.0005 inch per inch per minute through yielding, then 0.01 inch per inch per minute to fracture. Analyses 26.4% W, 0.106% Zr, and 0.033% C.
(b) 0.1 per cent offset.
(c) Analyses 25.1% W, 0.11% Zr, and 0.051% C.



Sheet rolled in air with a relatively low finishing temperature.

Heat 4052-L, analyses 25.4% W, 0.10% Zr, and 0.037% C.

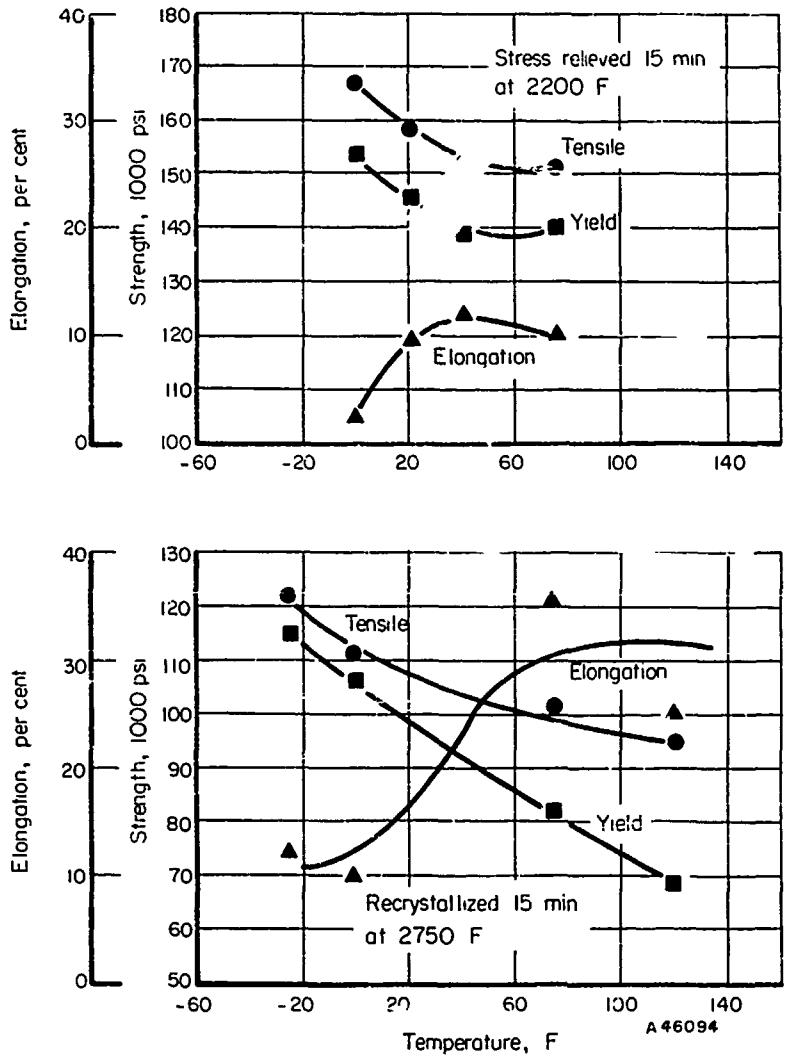
FIGURE A-153. LOW-TEMPERATURE TENSILE PROPERTIES OF LONGITUDINAL STRESS-RELIEVED AND RECRYSTALLIZED WZM SHEET (0.050 INCH)[4]



Sheet rolled in air with a relatively high finishing temperature.

Heat 4052-H, analyses 25.4% W, 0.10% Zr, and 0.037% C.

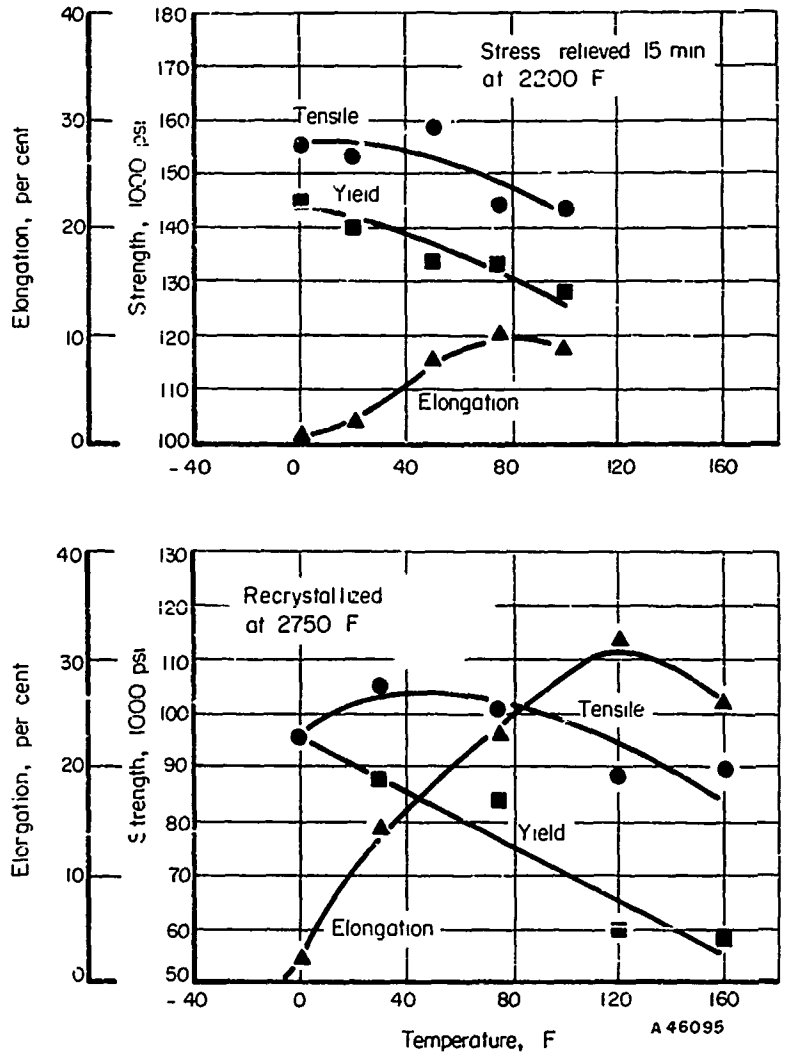
FIGURE A-153. (CONTINUED)



Sheet rolled in air with a relatively low finishing temperature.

Heat 4052-L, analyses 25.4% W, 0.10% Zr, and 0.037% C

FIGURE A-154. LOW-TEMPERATURE TENSILE PROPERTIES OF TRANSVERSE STRESS-RELIEVED AND RECRYSTALLIZED WZM SHEET (0.050 INCH)[4]



Sheet rolled in air with a relatively high finishing temperature.

Heat 4052-H, analyses 25.4% W, 0.10% Zr, and 0.037% C.

FIGURE A-154. (CONTINUED)

TABLE A-113. CREEP AND STRESS-RUPTURE PROPERTIES OF WZM BAR AT 1800 AND 2400 F[a][2]

Condition	Temperature, F	Stress, 1000 psi	Minimum Creep Rate, per cent/hour	Rupture Time, hours	Elongation, per cent	Reduction in Area, per cent
Stress relieved, 1 hour 2000 F	1800	87.0	--	1.3	20	75.4
		80.0	--	18.0	20	78.8
		55.0	--	35.7[b]	0.5	0.8
	2400	16.0	--	5.2	23	61.1
		14.0	0.168	28.5	--	91.9
Recrystallized, 1 hour 2600 F	1800	39.0	5.52	1.2	55	89.7
		38.4	1.86	1.5	53	87.9
		34.0	0.022	19.6	56	90.7
	2400	16.0	0.62	15.8	69	93.3
		13.0	0.080	65.8	64	95.5

(a) Analyses 26.4% W, 0.106% Zr, and 0.033% C.
(b) Test discontinued.

TABLE A-114. 1- AND 10-HOUR RUPTURE STRENGTHS OF WZM BAR AT 1800 AND 2400 F[a][2]

Condition	Temperature, F	Stress, 1000 psi, to Produce Rupture	
		1 Hour	10 Hours
Stress relieved, 1 hour 2000 F	1800	87.5	81.5
	2400	18.3	15.2
Recrystallized, 1 hour 2600 F	1800	39.2	35.1
	2400	23.4	16.9

(a) Analyses 26.4% W, 0.106% Zr, and 0.033% C.

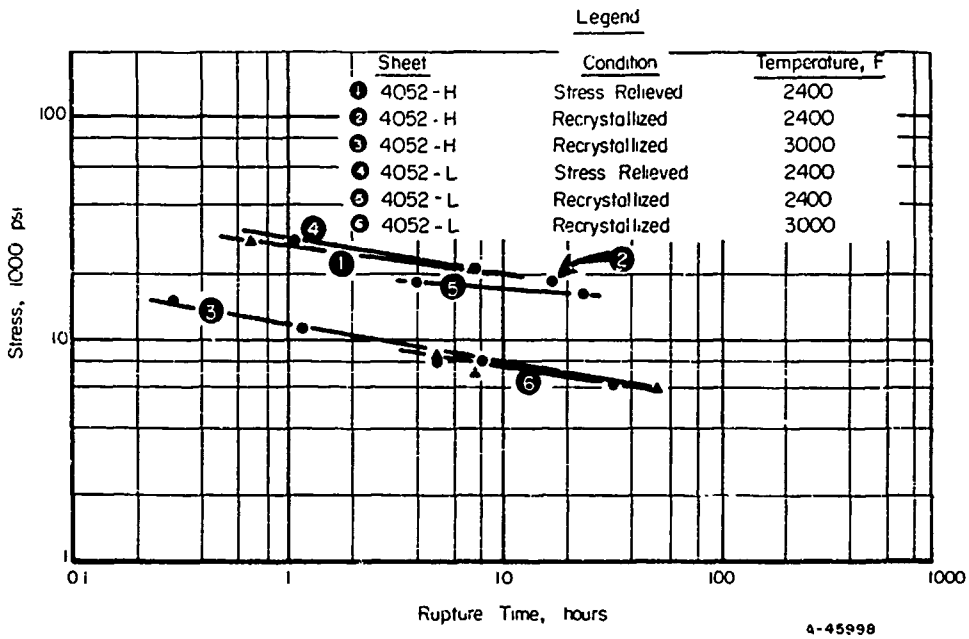


FIGURE A-155. STRESS-RUPTURE BEHAVIOR OF STRESS-RELIEVED AND RECRYSTALLIZED WZM SHEET AT 2400 AND 3000 F[4]

4052-L sheet rolled in air with a relatively low finishing temperature.

4052-H sheet rolled in air with a relatively high finishing temperature.

Analyses 25.4% W, 0.10% Zr, and 0.037% C.

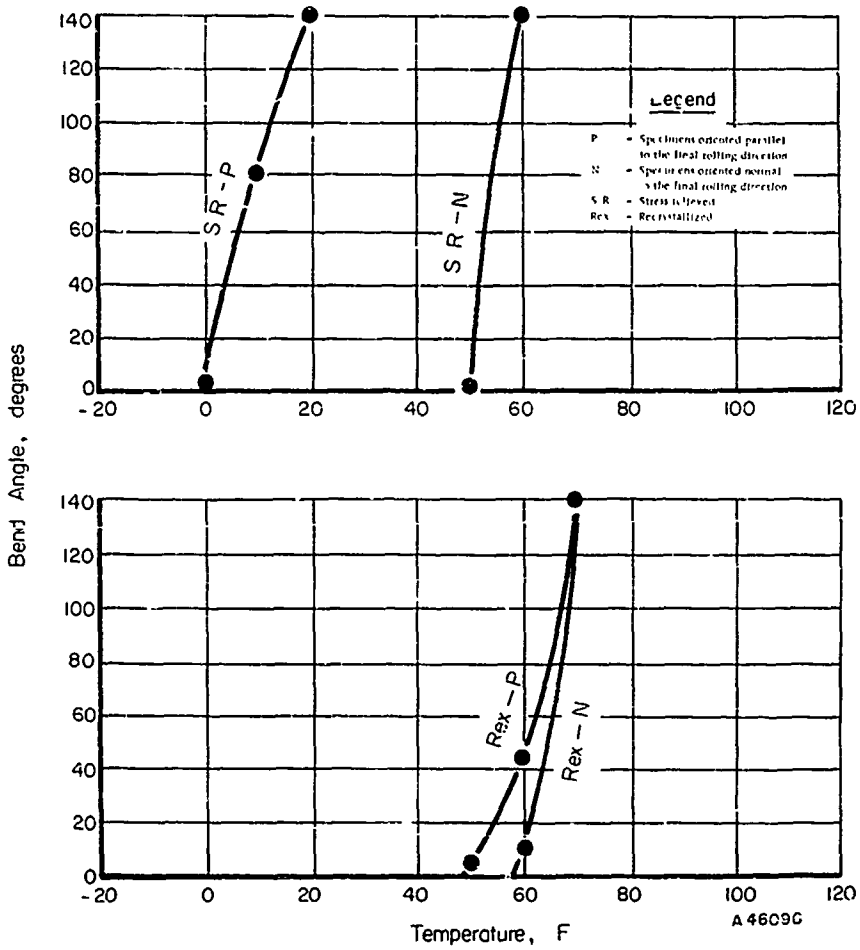


FIGURE A-156. BEND-DUCTILITY BEHAVIOR OF STRESS-RELIEVED AND RECRYSTALLIZED WZM SHEET (0.051 INCH)[4]

Sheet rolled in air with a relatively low finishing temperature.

Heat 4052-L, analyses 25.4% W, 0.10% Zr, and 0.037% C.

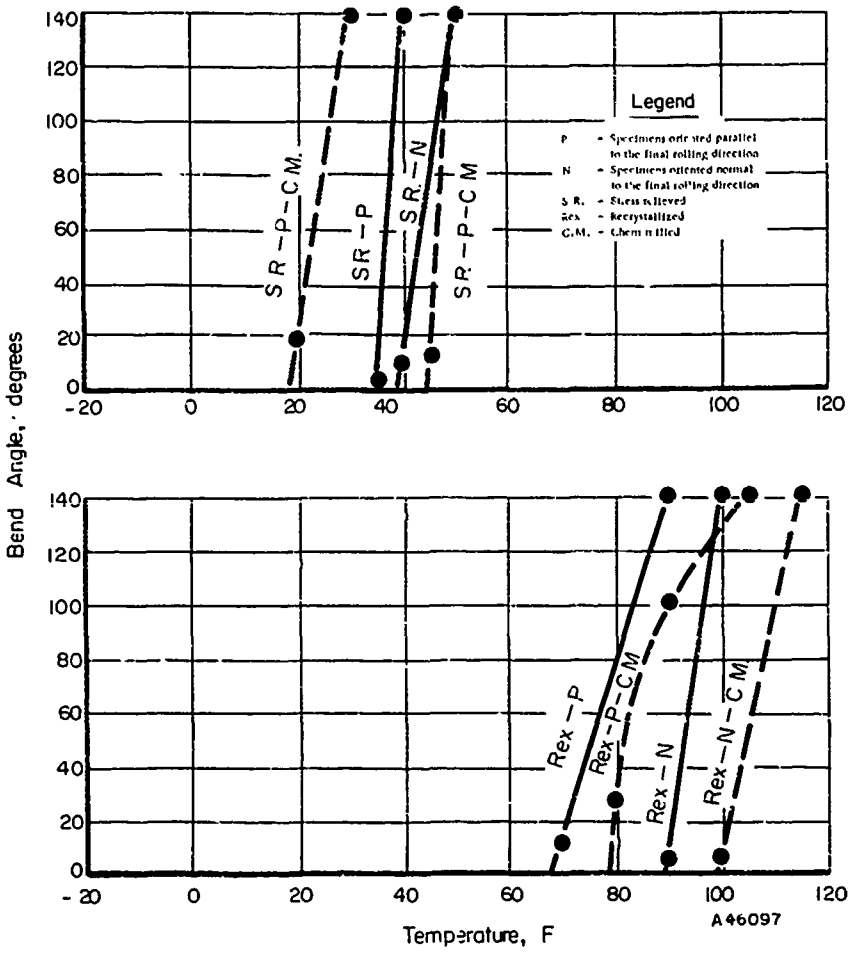


FIGURE A-157. EFFECT OF TEMPERATURE, THERMAL TREATMENT, AND SURFACE CONDITION ON THE BEND DUCTILITY OF WZM SHEET (0.051 INCH)[4]

Sheet rolled in air with a relatively high finishing temperature.

Specimens chemically milled to 0.048 inch.

Heat 4052-H, analyses 25.4% W, 0.10% Zr, and 0.037% C.

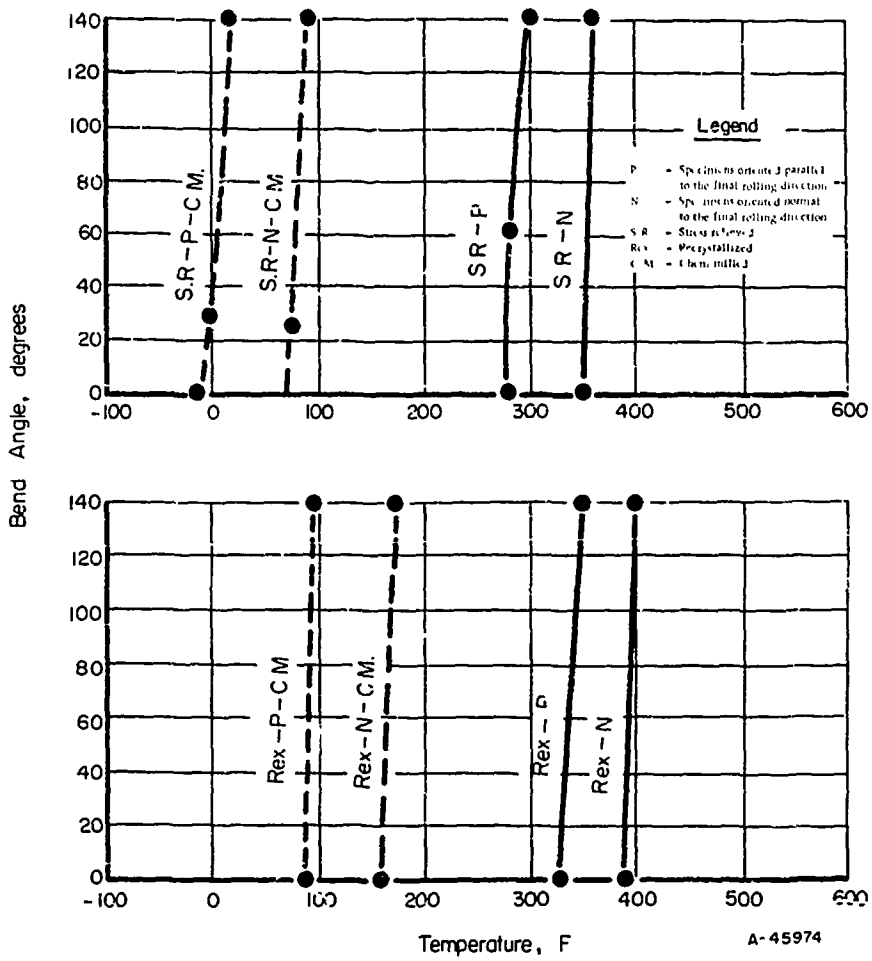


FIGURE A-158. EFFECT OF TEMPERATURE, THERMAL TREATMENT, AND SURFACE CONDITION ON THE BEND DUCTILITY OF WZM SHEET (0.054 TO 0.062 INCH)[4]

Rolled in InFab facility.

Specimens chemically milled 0.040 inch.

Heat 4052-I, analyses 25.4% W, 0.10% Zr, and 0.037% C.

4. Metallurgical Properties

a. Fabricability: successful extrusion temperatures for ingot range from 3200 to 4000 F with reduction ratios of up to 10.1 at 4000 F[5]

b. Transition Temperature: <RT to 400 F, depending upon form, fabrication history, thermal treatment, and surface condition[2-4]

c. Stress-relief temperature: 1 hour at 2000 F for bar material[2]; 1/4 hour at 2200 F for sheet (0.050 inch) material[4]

d. Recrystallization temperature: 1 hour at 2600 F for bar material[2]; 1/4 hour at 2750 to 2800 F for sheet (0.05 inch) material[4]

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. Semchyshen, M., and Barr, R. Q., "Extrusion and Mechanical Properties of Some Molybdenum- and Tungsten-Base Alloys", Climax Molybdenum Co., ASD TR 61-193 (May, 1961).

3. Semchysher, M., McArdle, G. D., and Barr, R. Q., "Development of Molybdenum-Base Alloys", Climax Molybdenum Co., WADC TR 59-280 (October, 1959).

4. McArdle, G. D., Barr, R. Q., and Semchyshen, M., "Investigation Molybdenum- and Tungsten-Base Alloy Sheet Materials", Climax Molybdenum Co., Contract No. NOw 61-0581-d, Final Report (January 15, 1963).

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

Mo-30W

1. Identification of Material

   a. Chemical composition: Mo-30W

   b. Forms available: ingot and fabricated shapes

2. Physical Properties

   a. Melting point: ~5150 F[1]

   b. Density: 0.43 lb/in.^{3}[2]

   c. Electrical resistivity: specific resistivity at room temperature is about 0.06 ohm/mm^2/m; the temperature coefficient of resistivity is 1.8×10^{-3}/F[2]

3. Mechanical Properties

   a. Tensile Properties at Room Temperature

      Ultimate tensile strength: Tables A-115 and A-116

      Tensile yield strength: Tables A-115 and A-116

      Elongation: Tables A-115 and A-116

      Reduction in area: Table A-115

      Modulus of elasticity: ~50×10^6 psi[2]

   b. Effect of Temperature on Tensile Properties

      Ultimate tensile strength: Table A-117

      Elongation: Table A-117

      Reduction in area: Table A-117

   c. Creep and Stress-Rupture Properties

      Table A-118

   d. Other Selected Mechanical Properties

      Hardness: Tables A-119 and A-120

TABLE A-115. ROOM-TEMPERATURE TENSILE PROPERTIES OF Mo-30W BAR (1/2-INCH SQUARE)[a][2]

Condition	Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation, per cent	Reduction in Area, per cent
Stress relieved, 2000 F	121.5	106.9	26	40
Recrystallized, 2600 F	83.8	69.1	12	10

(a) Analyses 28.91% W and 0.023% C.

TABLE A-116. TYPICAL ROOM-TEMPERATURE TENSILE DATA FOR ARC-CAST STRESS-RELIEVED Mo-30W ROUND BAR PRODUCED BY CLIMAX[a][3]

Diameter, inches	Average Tensile Strength, 1000 psi	Average Yield Strength (0.2% Offset), 1000 psi	Average Elongation in 1 Inch, per cent
1/2	104	96	20
5/8	100	88	15
3/4	93	78	10
7/8	100	94	10
1	106	94	7
1-1/2	101	90	6
1-3/4	88	73	1
2	93	82	6
2-3/4	91	75	10

(a) Cold Water Production Facility. All data from 6-inch-diameter arc-cast ingots covering a 2-year period. Material stress relieved 1/4 to 1 hour at 2200 to 2350 F. Test rate 0.002 inch per inch per minute in the elastic range, then 0.05 inch per inch per minute to fracture.

TABLE A-117. TENSILE PROPERTIES OF Mo-30W BAR (1/2-INCH SQUARE) AT 1800 F[a][2]

Condition	Tensile Strength, 1000 psi	Elongation, per cent	Reduction in Area, per cent
Stress relieved, 2000 F	65.7	25	77
Recrystallized, 2600 F	32.4	83	90

(a) Analyses 28.91% W and 0.023% C.

TABLE A-118. CREEP AND STRESS-RUPTURE PROPERTIES OF Mo-30W AT 1800 F[a][2]

Stress, 1000 psi	Creep Rate, per cent/hour	Rupture Time, hours	Elongation, per cent	Reduction in Area, per cent
60	17	1.6	13.9	84.8
50	0.12	28.1	17.2	84.5

(a) These values give an estimated 100-hour rupture strength of 47,000 psi. Analyses 28.91% W and 0.023% C.

TABLE A-119. TYPICAL ROOM-TEMPERATURE HARDNESS DATA FOR ARC-CAST Mo-30W ROUND BAR PRODUCED BY CLIMAX[a][3]

Diameter, inches	Average Hardness, DPH
1/2	256
5/8	250
3/4	243
7/8	260
1	275
1-1/2	264
1-3/4	253
2	257
2-3/4	246

(a) Cold Water Production Facility. All data from 6-inch-diameter arc-cast ingots covering a 2-year period. Material stress relieved 1/4 hour to 1 hour at 2250 to 2350 F.

TABLE A-120. HOT-HARDNESS OF AS-CAST Mo-30W[2]

Temperature, F	Hot Hardness, DPH
RT	198
2000	70
2200	60
2400	50
2600	40
2800	32
3000	27

4. Metallurgical Properties

a. Fabricability: material has been successfully extruded and forged; a satisfactory forging temperature is 2300 F, requires more reheatings and higher working pressures than unalloyed molybdenum[2]

b. Transition temperature: <RT for bar material[2,3]

c. Weldability: material has been successfully joined by welding[4]

d. Stress-relief temperature: 1/4 to 1 hour at 2200 to 2350 F[3]

e. Recrystallization temperature. 2600 F[2]

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) "Climelt Molybdenum – 30% Tungsten Alloy", Climax Molybdenum Co., Technical Note (February, 1959).

(3) Private communication from G. D. McArdle, Climax Molybdenum Co. (1963).

(4) Private communication from F. Nair, Climax Molybdenum Co. (1963).

Mo-50W

1. Identification of Material

   a. Chemical composition: Mo-50W

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

2. Physical Properties

   a. Melting point: ~5450 F[1]

   b. Density: 0.483 lb/in.^{3} (calculated)

3. Mechanical Properties

   a. Tensile Properties at Room Temperature

      Ultimate tensile strength: Table A-121

      Tensile yield strength: Table A-121

      Elongation: Table A-121

      Reduction in area: Table A-121

   b. Effect of Temperature on Tensile Properties

      Ultimate tensile strength: Table A-122

      Elongation: Table A-122

      Reduction in area: Table A-122

   c. Creep and Stress-Rupture Properties

      Tables A-123 and A-124

   d. Other Selected Mechanical Properties

      a. Bend ductility: Figures A-159 and A-160

TABLE A-121. ROOM-TEMPERATURE TENSILE PROPERTIES OF Mo-50W BAR[a](2)

Condition	Tensile Strength, 1000 psi	Yield Strength (0.1% Offset), 1000 psi	Elongation, per cent	Reduction in Area, per cent
Stress relieved, 1 hour 2000 F	144.0	133.8	14	13.1
Recrystallized, 1 hour 2700 F	97.7	--	0	0

(a) Test rate 0.0005 inch per inch per minute through yielding, then 0.01 inch per inch per minute to fracture. Analyses 49.3%W and 0.008%C.

TABLE A-122. TENSILE PROPERTIES OF Mo-50W BAR AT 1800 AND 2400 F[a](2)

Condition	Temperature, F	Tensile Strength, 1000 psi	Yield Strength (0.1% Offset), 1000 psi	Elongation, per cent	Reduction in Area, per cent
Stress relieved, 1 hour 2000 F	1800	83.0	49.7	26	83.8
	2400	50.1	20.[illegible]	37	93.6
Recrystallized, 1 hour 2700 F	1800	44.6	17.8	57	87.7
	2400	25.8	16.2	76.5	81.3

(a) Test rate 0.0005 inch per inch per minute through yielding, then 0.01 inch per inch per minute to fracture. Analyses 49.3%W and 0.008%C.

TABLE A-123. CREEP AND STRESS-RUPTURE PROPERTIES OF Mo-50W BAR AT 1800 AND 2400 F[a][2]

Condition	Temperature, F	Stress, 1000 psi	Minimum Creep Rate, per cent/hour	Rupture Time, hours	Elongation, per cent	Reduction in Area, per cent
Stress relieved, 1 hour 2000 F	1800	69.1	--	0.4	31	81.7
		61.9	--	3.7	28	51.9
	2400	30.0	--	0.4	37	85.9
		16.0	0.95	10.0	56	70.3
Recrystallized, 1 hour 2700 F	1800	36.0	5.76	3.3	58	89.8
		[illegible]		19.1	50	72.7
	2400	19.0	--	2.1	56	23.2
		15.0	--	10.4	118	94.6

(a) Analyses 49.3%W and 0.008%C.

TABLE A-124. 1- AND 10-HOUR RUPTURE STRENGTHS OF Mo-50W BAR AT 1800 AND 2400 F[a][2]

Condition	Temperature, F	Stress, 1000 psi, to Produce Rupture	
		1 Hour	10 Hours
Stress relieved, 1 hour 2000 F	1800	66.0	58.5
	2400	25.0	16.0
Recrystallized, 1 hour 2700 F	1800	38.5	33.0
	2400	21.2	15.1

(a) Analyses 49.3%W and 0.008%C.

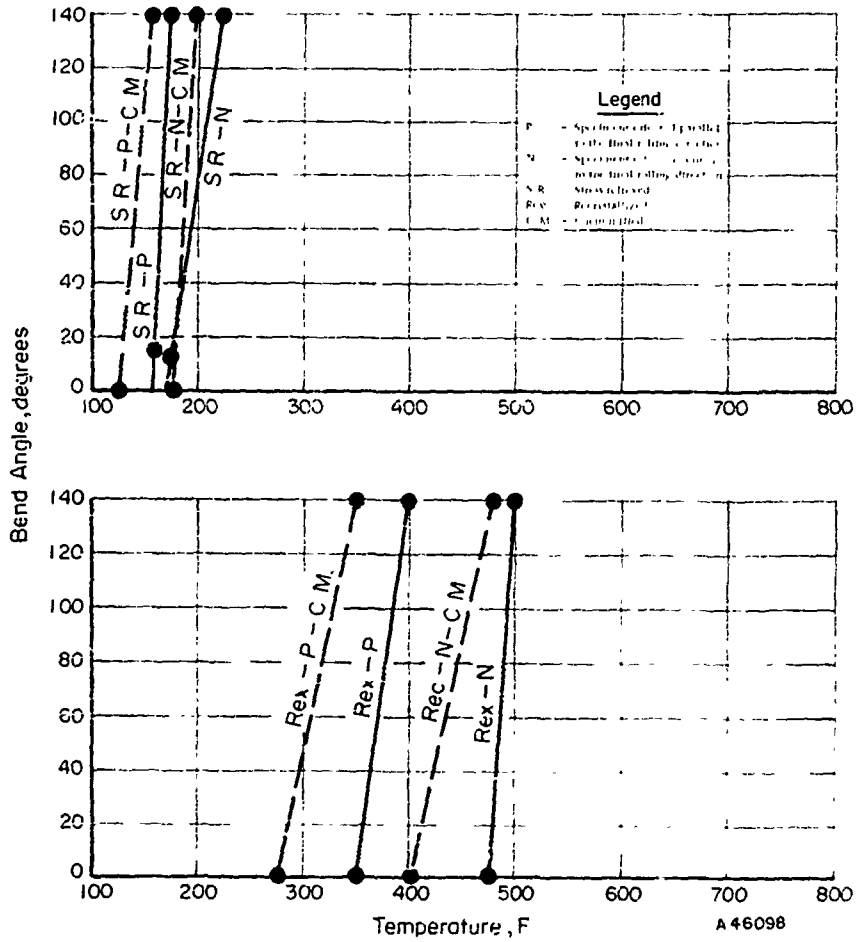


FIGURE A-159. EFFECT OF TEMPERATURE, THERMAL TREATMENT, AND SURFACE CONDITION ON THE BEND DUCTILITY OF Mo-50W SHEET (0.048 INCH)[3]

Sheet rolled in air with a relatively low finishing temperature.

Specimens chemically milled to 0.045 inch.

Heat 4056-L, analyses 49.1% W and 0.014% C.

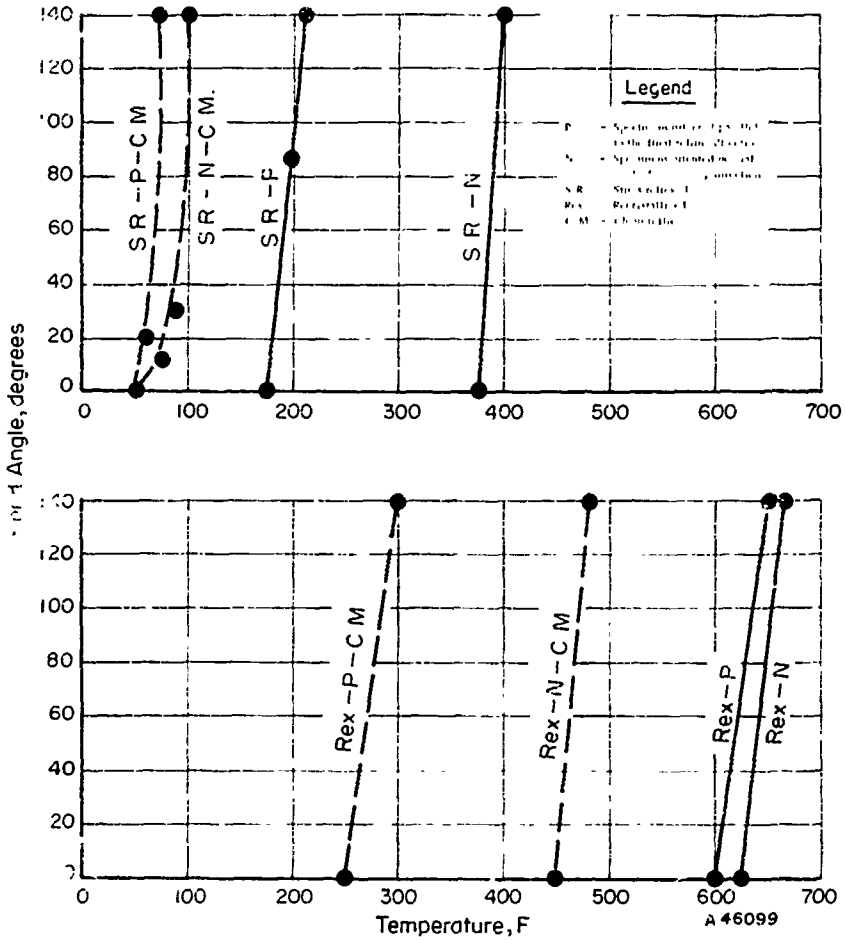


FIGURE A-160. EFFECT OF TEMPERATURE, THERMAL TREATMENT, AND SURFACE CONDITION ON THE BEND DUCTILITY OF Mo-50W SHEET (0.039 TO 0.044 INCH)[3]

Rolled in InFab facility.

Specimens chemically milled to 0.036 inch.

Heat 4056-I, analyses 49.1% W and 0.014% C

4. Metallurgical Properties

a. Fabricability. arc-cast ingots can be extruded to sheet bar at 3500 to 4000 F using reduction ratios of up to 8:1; sheet bar can be rolled to intermediate gage thickness (1/8 inch) at 2400 to 2800 F, final sheet rolling to 0.050 inch can be done at 2400 F[3]

b. Transition temperature: ~RT to 625 F, depending upon form, fabrication history, thermal treatment and surface condition[2, 3]

c. Stress-relief temperature. 1 hour at 2000 F for bar material[2]

d. Recrystallization temperature: 1 hour at 2700 F for bar material[2]; 1/4 hour at 2800 F for sheet (0.050-inch) material[3]

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. Semchyshen, M., and Barr, R. Q., "Extrusion and Mechanical Properties of Molybdenum- and Tungsten-Base Alloys", Climax Molybdenum Co., ASD TR 61-193 (May, 1961).

3. McArdle, G. D., Barr, R. Q., and Semchyshen, M., "Investigation of Molybdenum- and Tungsten-Base Alloy Sheet Materials", Climax Molybdenum Co., Contract No. NOw 61-0581-d, Final Report (January 15, 1963).

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 151035 $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 $[illegible])
127	Physical and Mechanical Properties of Tungsten and Tungsten-Base Alloys, March [illegible]
128	A Summary of Comparative Properties of Air-Melted and Vacuum-Melted Steels and Superalloys, March 28 1960 (PB 151086 $1.75)
129	Physical Properties of Some Nickel Base Alloys, May 20 1960 (PB 151086 $2.75)
130	Elevated 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 $2.50)
134	Strain Aging of Refractory Metals, August 12 1960 (PB 151092 $1.75)
135	Design Information on [illegible] Stainless Steel for Aircraft and Missiles, August 22, 1960 (PB 151093 $1.75)

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 15, 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 Prospection, 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 1, 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 257729 $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 151081 $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 266123 $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 265339 $2.50)
167	Summary of the Fifth Meeting of the Refractory Composites Working Group, March 12, 1962 (AD 274804 $2.50)
168	Beryllium for Structural Applications, 1958-1960, May 13, 1962 (AD 278723 $3.50)
169	The Effect of Molten Alkali Metals on Contaminated Metals and Alloys at High Temperatures, May 18, 1962 (AD 282932 $1.50)
170	Chemical Vapor Deposition, June 4, 1962 (AD 28[illegible] $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 16, 1962, Vol. I (AD 294345 $3.00)
177	Thermal Radiative Properties of Selected Materials, November 16, 1962, Vol. II (AD 294346 $4.50)
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

Best Available Copy

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

Best Available Copy

Battelle Memorial Institute, Defense Metals Information Center, Columbus, Ohio. THE ENGINEERING PROPERTIES OF MOLYBDENUM AND MOLYBDENUM ALLOYS, by F. F. Schmidt and H. R. Ogden. September 20, 1963. [288] pp incl. illus., tables, refs. DMIC Report 190. [AF 33(616)-7747]

Unclassified report

This report presents the results of a state-of-the-art survey covering molybdenum and nine of its most promising 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. Molybdenum
2. Physical Properties
3. Mechanical Properties
4. Metallurgical Properties

I. Battelle Memorial Institute
II. Defense Metals Information Center
III. Contract AF 33(616)-7747

UNCLASSIFIED

Battelle Memorial Institute, Defense Metals Information Center, Columbus, Ohio. THE ENGINEERING PROPERTIES OF MOLYBDENUM AND MOLYBDENUM ALLOYS, by F. F. Schmidt and H. R. Ogden. September 20, 1963. [288] pp incl. illus., tables, refs. DMIC Report 190. [AF 33(616)-7747]

Unclassified report

This report presents the results of a state-of-the-art survey covering molybdenum and nine of its most promising 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. Molybdenum
2. Physical Properties
3. Mechanical Properties
4. Metallurgical Properties

I. Battelle Memorial Institute
II. Defense Metals Information Center
III. Contract AF 33(616)-7747

UNCLASSIFIED

Battelle Memorial Institute, Defense Metals Information Center, Columbus, Ohio. THE ENGINEERING PROPERTIES OF MOLYBDENUM AND MOLYBDENUM ALLOYS, by F. F. Schmidt and H. R. Ogden. September 20, 1963. [288] pp incl. illus., tables, refs. DMIC Report 190. [AF 33(616)-7747]

Unclassified report

This report presents the results of a state-of-the-art survey covering molybdenum and nine of its most promising 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. Molybdenum
2. Physical Properties
3. Mechanical Properties
4. Metallurgical Properties

I. Battelle Memorial Institute
II. Defense Metals Information Center
III. Contract AF 33(616)-7747

UNCLASSIFIED

Battelle Memorial Institute, Defense Metals Information Center, Columbus, Ohio. THE ENGINEERING PROPERTIES OF MOLYBDENUM AND MOLYBDENUM ALLOYS, by F. F. Schmidt and H. R. Ogden. September 20, 1963. [288] pp incl. illus., tables, refs. DMIC Report 190. [AF 33(616)-7747]

Unclassified report

This report presents the results of a state-of-the-art survey covering molybdenum and nine of its most promising 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. Molybdenum
2. Physical Properties
3. Mechanical Properties
4. Metallurgical Properties

I. Battelle Memorial Institute
II. Defense Metals Information Center
III. Contract AF 33(616)-7747

UNCLASSIFIED