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MECHANICAL PROPERTIES OF ELECTRON-BEAM-MELTED MOLYBDENUM AND DILUTE MOLYBDENUM-RHENIUM ALLOYS

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16. Abstract

A study of molybdenum and three dilute molybdenum-rhenium alloys was undertaken to determine the effects of rhenium on the low-temperature ductility and other mechanical properties of molybdenum. Alloys containing 3.9, 5.9, and 7.7 atomic percent rhenium all exhibited lower ductile-brittle transition temperatures than did the unalloyed molybdenum. The maximum improvement in the annealed condition was observed for molybdenum - 7.7 rhenium, which had a ductile-brittle transition temperature approximately 200° C (360° F) lower than that for unalloyed molybdenum. Rhenium additions also increased the low- and high-temperature tensile strengths and the high-temperature creep strength of molybdenum. The mechanical behavior of dilute molybdenum-rhenium alloys is similar to that observed previously for dilute tungsten-rhenium alloys.

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SUMMARY

A study of molybdenum and three dilute molybdenum-rhenium alloys was undertaken to determine the effects of rhenium at concentrations less than 10 atomic percent on the low-temperature ductility, low- and high-temperature tensile properties, high-temperature creep properties, and recrystallization and grain-growth behavior of molybdenum. Materials investigated included electron-beam-melted unalloyed molybdenum and molybdenum alloys containing 3.9, 5.9, and 7.7 atomic percent rhenium. Significant improvements in low-temperature ductility were observed with rhenium alloying. The bend and tensile ductile-brittle transition temperatures in both the worked and recrystallized conditions decreased with increasing rhenium content. Maximum ductility improvement was observed for the molybdenum - 7.7-rhenium alloy, which exhibited a tensile ductile-brittle transition temperature in the recrystallized condition of -170° C (-270° F) compared with 65° C (150° F) for unalloyed molybdenum.

Rhenium alloying increased the low-temperature and high-temperature tensile strengths and the high-temperature creep strength of molybdenum. At 1315° C (2400° F), an approximately 60-percent increase in tensile strength was obtained by alloying molybdenum with 7.7 atomic percent rhenium.

The recrystallization temperature of molybdenum was increased and grain sizes decreased by alloying it with rhenium.

The mechanical property trends of dilute molybdenum-rhenium alloys are similar to those observed previously for dilute tungsten-rhenium alloys.

INTRODUCTION

Although rhenium is better known for its remarkable "ductilizing" effect in molybdenum - 35-rhenium and tungsten - 26-rhenium alloys (ref. 1), it also promotes reduced hardness and improved low-temperature ductility in the Group VIA elements at alloying levels below 10 atomic percent (ref. 2). This latter effect is termed "solution softening" and is also promoted to lesser degrees by elements other than rhenium; that is, by the platinum-group metals.

Recent studies of tungsten-rhenium alloys showed that additions of 2 to 4 atomic percent rhenium to tungsten reduced the ductile-brittle bend transition temperature by about 150° C (270° F) (ref. 3). Since molybdenum is similar in many respects to tungsten and also exhibits reduced low-temperature hardness on dilute rhenium alloying (ref. 4), similar reductions in the ductile-brittle transition temperature can be expected in dilute molybdenum-rhenium alloys.

The present study was undertaken primarily to determine the effects of small rhenium additions on the low-temperature ductility of molybdenum. A secondary objective was to characterize the mechanical properties of dilute molybdenum-rhenium alloys and their recrystallization and grain-growth behavior. Ingots of unalloyed molybdenum and three molybdenum-rhenium alloys were electron-beam melted, fabricated to rod and sheet, and evaluated by bend, tensile, and creep tests and by optical metallography.

EXPERIMENTAL PROCEDURES

Material Preparation

The starting materials consisted of -325 mesh commercially pure (99.97 weight percent) molybdenum powder and -200 mesh commercially pure (99.98 weight percent) rhenium powder. The blended powders were compacted isostatically into electrodes measuring nominally 3 centimeters ($1\frac{1}{8}$ in.) in diameter by 61 centimeters (24 in.) in length. The electrodes were then triple electron-beam melted into 6-centimeter- ($2\frac{1}{2}$-in.-) diameter ingots ranging from 10 to 15 centimeters (4 to 6 in.) in length.

Fabrication

Fabrication details for the four ingots are summarized in table I. The extrusion billets measured 5 centimeters (2 in.) in diameter by 8 to 13 centimeters (3 to 5 in.) in length and were extruded at 1425° to 1540° C (2600° to 2800° F). No difficulties were encountered with any of the extrusions. The extrusions were fabricated to rod and sheet, as indicated in table I.

Duplicate analysis on fabricated rod and sheet indicated moderately low oxygen, nitrogen, and carbon contents, as shown in table II. Rhenium contents of the three alloy ingots ranged from 3.9 to 7.7 atomic percent.

Evaluation

Bend test specimens measuring 0.8 by 2 centimeters (0.3 by 0.9 in.) were cut from the rolled sheets with a cutoff wheel. All specimens were electropolished in a 2-weight-percent aqueous sodium hydroxide solution to remove 75 to 125 micrometers (3 to 5 mils) of metal per side before bend testing. Heat treatment of selected specimens prior to bend testing was conducted in an induction-heated hydrogen-atmosphere tube furnace equipped with a tungsten - tungsten-25-rhenium thermocouple. Bend tests were performed over the temperature range of -195° to 150° C (-320° to 300° F), at a crosshead speed of 2.5 centimeters (1 in.) per minute over a bend radius of four times the specimen thickness (4T). A controlled liquid-nitrogen spray was used for tests at -30° C (-25° F) and lower, while dry-ice - acetone mixtures were used to obtain temperatures between -30° and 25° C (-25° and 75° F). For temperatures between 25° and 150° C (75° and 300° F), an air-atmosphere infrared-lamp furnace was used. The bend transition temperature is defined as the lowest temperature at which a specimen could be bent 90° without fracture.

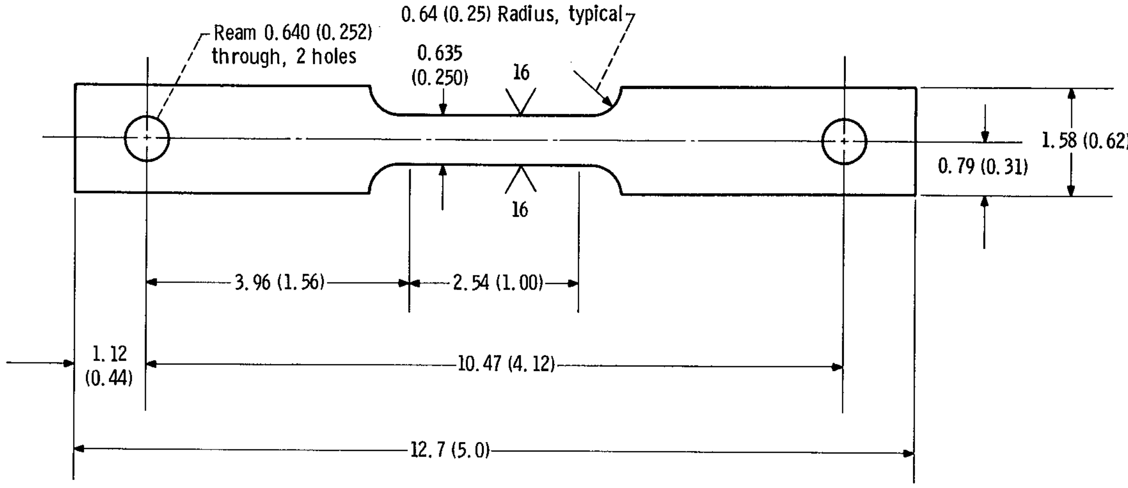
Rod or sheet tensile specimens were machined from each alloy to study the low- and high-temperature tensile properties and high-temperature creep properties. Dimensions of these specimens are given in figure 1.

Specimens for low-temperature testing were electropolished to remove 75 to 125 micrometers (3 to 5 mils) per side prior to testing at a crosshead speed of 0.13 centimeter (0.05 in.) per minute.

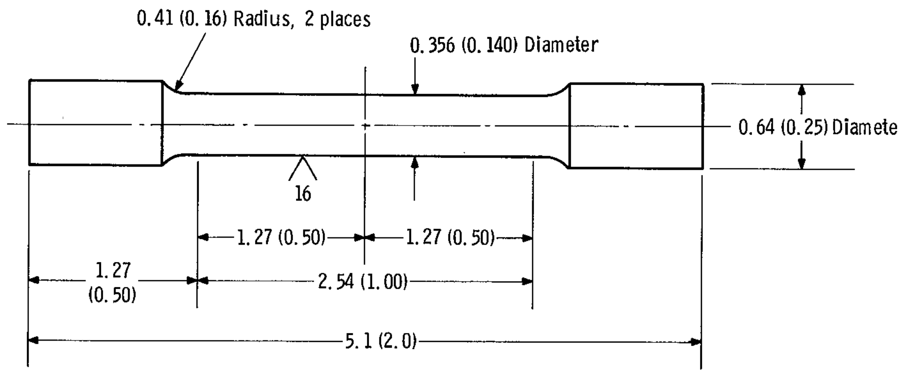
Tensile tests at 980° to 1650° C (1800° to 3000° F) were conducted at a chamber pressure of 10^{-3} N/m^{2} (10^{-5} torr) in a water-cooled stainless-steel vacuum unit equipped with a tantalum sleeve heater. Crosshead speed was 0.13 centimeter (0.05 in.) per minute.

Single-load and step-load creep tests were conducted in a conventional beam-loaded unit equipped with a water-cooled vacuum shell and a tantalum heater similar to that used for tensile testing. Specimen extensions were followed by linear variable differential transformer (LVDT) measurements of the differential motion between two pairs of tungsten rods attached to opposite ends of the creep specimens.

Annealing studies were conducted on sheet and rod specimens to determine the temperature for 100-percent recrystallization in 1 hour and the grain sizes after recrystallization. Specimens were heated for 1 hour at 540° to 1980° C (1000° to 3600° F) and examined metallographically. The extent of recrystallization was visually estimated, while grain sizes were determined by the line-intercept method.



(a) Sheet tensile specimen.



(b) Buttonhead tensile specimen.

Figure 1. - Configurations of tensile specimens. Dimensions are in centimeters (in.).

RESULTS AND DISCUSSION

Low-Temperature Bend Properties

Bend transition temperatures for unalloyed molybdenum and the three molybdenum-rhenium alloys in the as-rolled condition and after annealing at 480° to 1370° C (900° to 2500° F) are given in table III. The bend transition temperatures in the as-rolled and recrystallized conditions are shown in figure 2 as functions of rhenium content.

Figure 2 shows that dilute rhenium additions effect significant reductions in the ductile-brittle transition temperature. In the annealed and as-rolled conditions, the addition of 6 atomic percent rhenium reduces the transition temperature of molybdenum

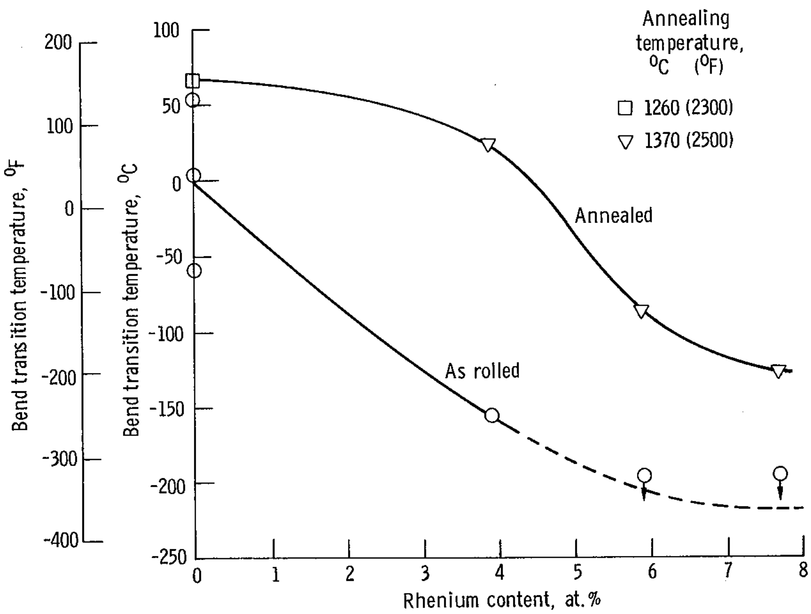


Figure 2. - Bend transition temperature for electron-beam-melted molybdenum and molybdenum-rhenium alloys.

by about 165° C (300° F). This reduction, in the as-rolled condition, is similar to that observed previously for tungsten-rhenium alloys (ref. 3). The transition temperatures for annealed molybdenum-rhenium alloys also follow the same trend as those of annealed (just recrystallized) tungsten-rhenium alloys in that they show a continuous decrease in transition temperature with increasing rhenium content. The transition temperatures for the molybdenum-rhenium alloys of the present investigation in the wrought and annealed conditions are also lower than those for similar electron-beam-melted-tungsten - rhenium alloys. For example, at the 6-atomic-percent-rhenium level, the transition temperature for molybdenum in the wrought condition is about 140° C (250° F) lower, and in the annealed condition, about 250° C (450° F) lower than that of tungsten.

Low-Temperature Tensile Properties

Low-temperature tensile properties were measured over the temperature range of -195° to 300° C (-320° to 580° F) in the worked and annealed conditions. Data from these tests are given in table IV.

The change in reduction in area as a function of temperature is shown in figure 3. This change is sharp for unalloyed molybdenum, the reduction in area increasing from 20 to 70 percent with a slight increase in test temperature. In contrast, the rhenium-containing alloys exhibit a more gradual change in reduction in area with temperature. The molybdenum alloys containing 5.9 and 7.7 atomic percent rhenium re-

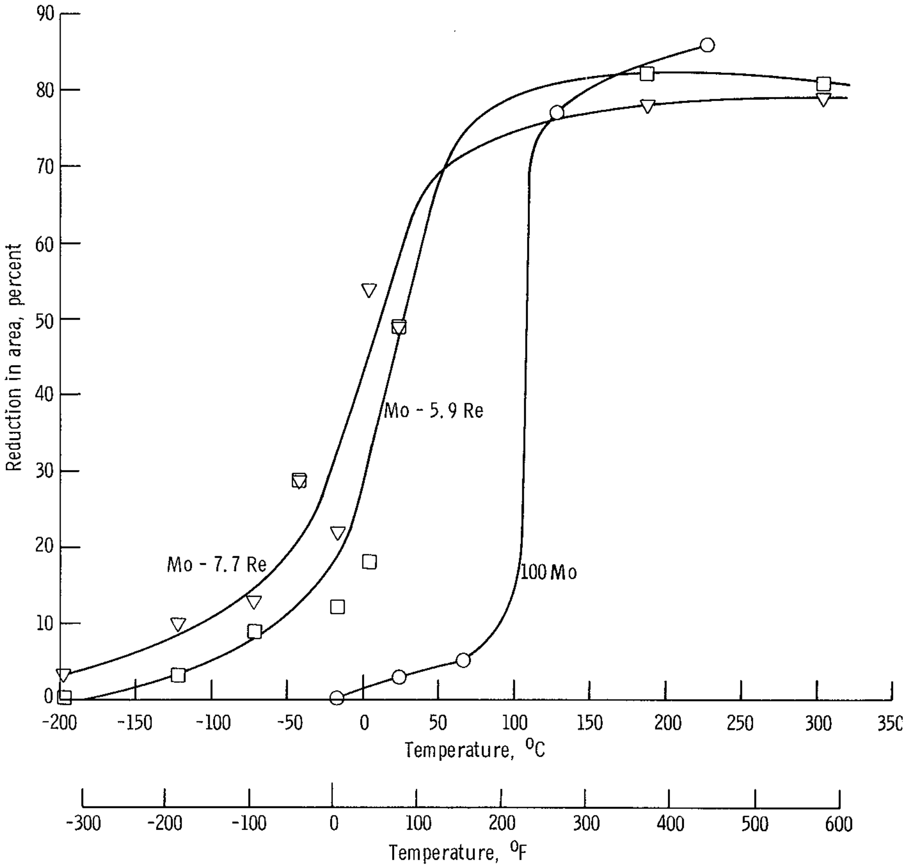


Figure 3. - Tensile reduction in area as a function of temperature for recrystallized molybdenum and molybdenum-rhenium alloys.

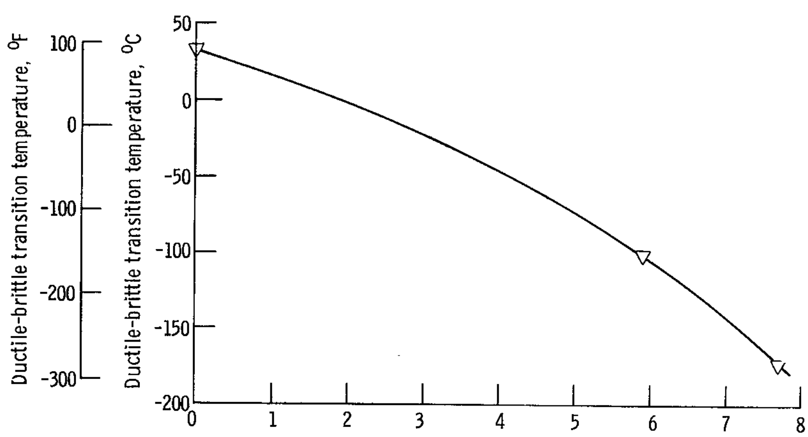


Figure 4. - Tensile ductile-brittle transition temperature as a function of rhenium content for annealed molybdenum and molybdenum-rhenium alloys.

quire a temperature increase of 70° to 100° C (125° to 180° F) for a similar ductility increase. This effect of rhenium on the sharpness of the ductile-brittle transition in molybdenum was previously observed in molybdenum and tungsten (ref. 5).

Rhenium effects a decrease in the tensile ductile-brittle transition temperature similar to that observed in bending. The change in transition temperature with rhenium content is shown in figure 4, where a 5-percent reduction in area is used as the criterion for ductility. The addition of 5.9 atomic percent rhenium decreases the transition temperature by about 140° C (250° F) in the annealed condition.

High-Temperature Tensile Properties

Tensile properties of unalloyed molybdenum and of the three molybdenum-rhenium alloys were measured over the temperature range of 980° to 1650° C (1800° to 3000° F), with results as given in table V.

Rhenium is a moderate strengthener for molybdenum at these temperatures, as shown in figure 5. The addition of 5 atomic percent rhenium approximately doubles the strength of molybdenum at 980° C (1800° F), while at 1650° C (3000° F), the addition of 7.7 atomic percent rhenium effects an approximately 50-percent increase in the ultimate strength.

Rhenium is approximately as strengthening in molybdenum as in tungsten, as shown by the modulus-compensated comparison of tensile strengths in figure 6. This similarity in strengths is not unexpected, considering the similarities in the molybdenum-

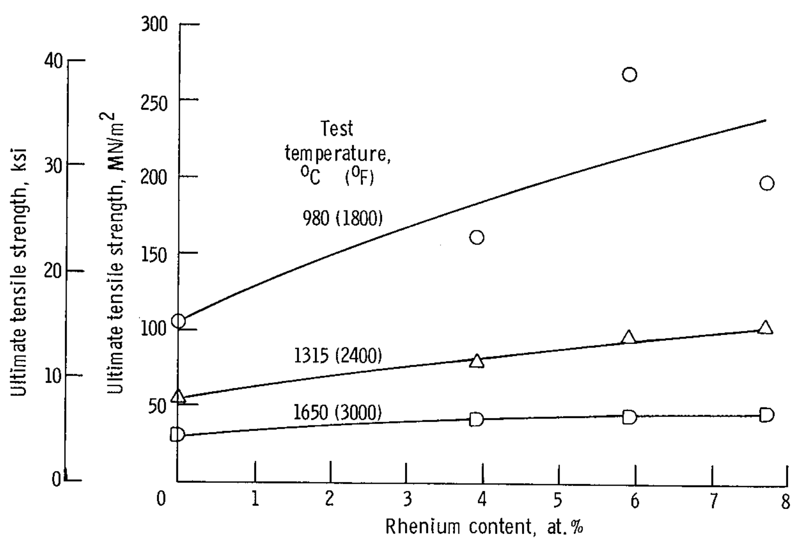


Figure 5. - Ultimate tensile strengths for annealed molybdenum and molybdenum-rhenium alloys at 980° to 1650° C (1800° to 3000° F).

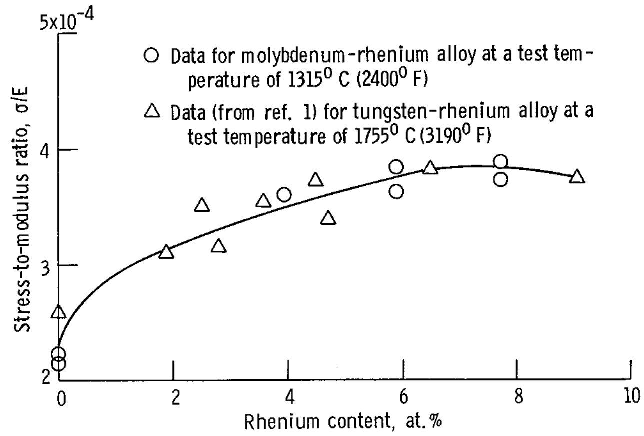


Figure 6. - Comparison of modulus-compensated tensile strengths for molybdenum-rhenium and tungsten-rhenium alloys at a homologous temperature of 0.551.

rhenium and tungsten-rhenium phase diagrams and in low-temperature mechanical properties.

High-Temperature Creep Properties

The creep properties of unalloyed molybdenum and of the three molybdenum-rhenium alloys were studied over the temperature range of 980° to 1650° C (1800° to 3000° F). Results are given in table VI and in figures 7 and 8.

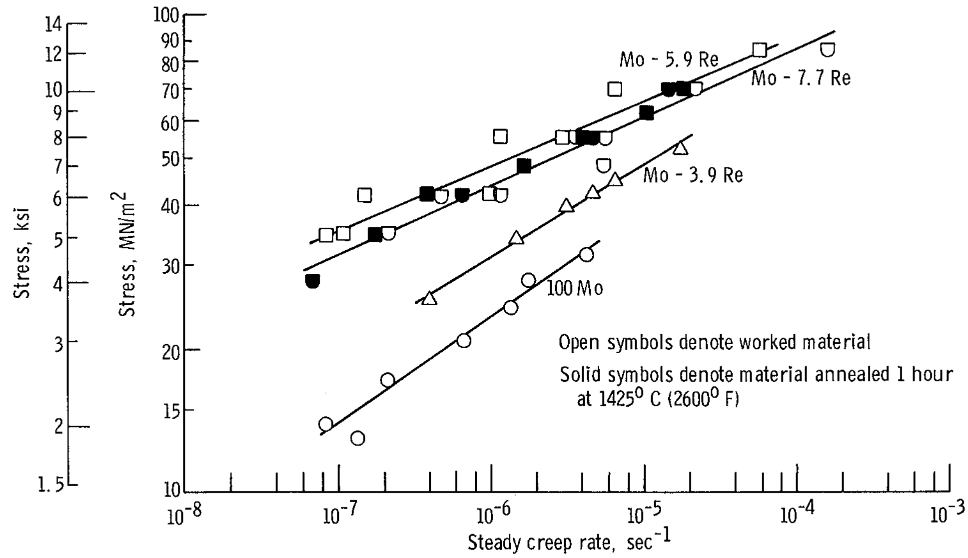


Figure 7. - Creep behavior of molybdenum and molybdenum-rhenium alloys at 1315° C (2400° F).

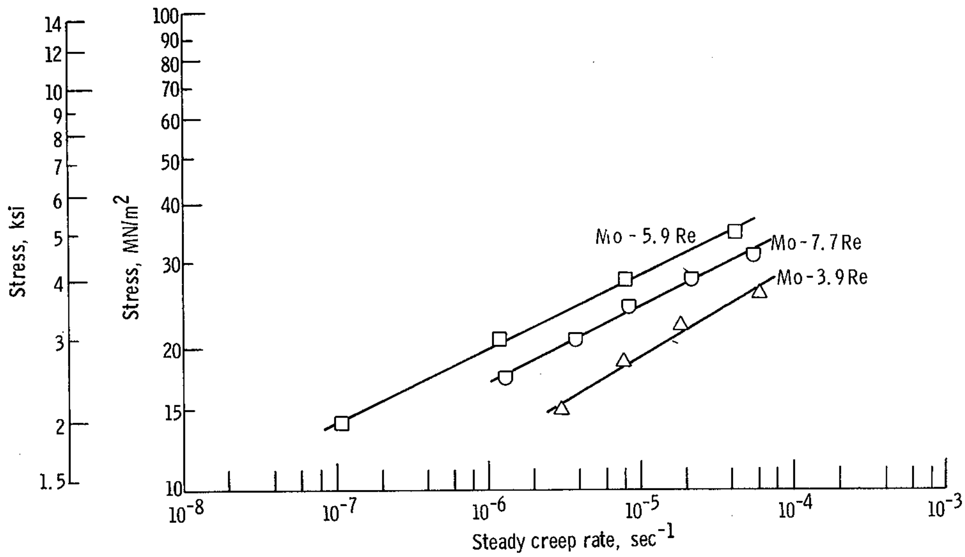


Figure 8. - Creep behavior of molybdenum-rhenium alloys at 1650° C (3000° F).

The data tend to follow the power law relation between creep rate and stress, expressed as

$$\dot{e} = k\sigma^{n}$$

where

$\dot{e}$ steady creep rate, sec^{-1}

k temperature dependent constant

σ stress, MN/m^2

n stress dependency

It is evident that the stress dependency tends to increase with increasing strength. For example, at 1315° C (2400° F), n is 4.8 for unalloyed molybdenum and increases to 7.5 for the molybdenum - 5.9-rhenium alloy, the strongest of the test materials at this temperature. This behavior is in contrast to the frequent observation of decreasing n with increasing alloy content (ref. 6).

It is further evident from the 1649°-C (3000°-F) data that creep strength in this temperature range increases with increasing alloy content to 5.9-atomic-percent rhenium, but then decreases when the rhenium content is increased further to 7.7 atomic percent. This strength behavior is similar to that of tungsten-rhenium alloys, which also show a creep-strength plateau.

Recrystallization and Grain Growth

The recrystallization and grain-growth characteristics of molybdenum and of the three molybdenum-rhenium alloys with 81 to 92 percent cold work were briefly evaluated with results as given in table VII.

Unalloyed molybdenum sheet exhibited a very low recrystallization temperature of 925° C (1700° F) for 100 percent recrystallization in 1 hour. The high purity of the electron-beam-melted molybdenum in the present study undoubtedly caused its low recrystallization temperature.

Alloying with 3.9 atomic percent rhenium increased the recrystallization temperature to 1260° C (2300° F). Since the recrystallization temperature of molybdenum sheet generally is lower than that of swaged rod, little or no change occurred in the recrystallization temperature of the alloy as the rhenium content was increased from 3.9 to 7.7 atomic percent.

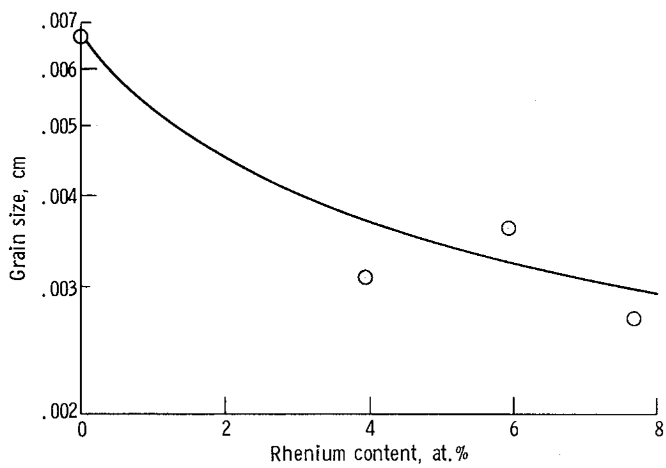


Figure 9. - Effect of rhenium content on grain size of electron-beam-melted molybdenum after annealing for 1 hour at 1425° C (2600° F).

Rhenium also tended to decrease the annealed grain size, as illustrated by the plot of grain size after annealing at 1425° C (2600° F) shown in figure 9.

These recrystallization and grain-growth trends as functions of rhenium content are very similar to those observed previously for tungsten-rhenium alloys and further attest to the similar physical behaviors in these two systems.

SUMMARY OF RESULTS

The following are the major results of this study of the mechanical properties of molybdenum alloys containing 3.9, 5.9, and 7.7 atomic percent rhenium:

1. High-purity molybdenum-rhenium alloys have ductile-brittle transition temperatures considerably lower than those for unalloyed molybdenum in both bend and tensile tests and in both the recrystallized and worked conditions. Of the three alloys of this study, the maximum improvement over unalloyed molybdenum is shown by the molybdenum - 7.7-atomic-percent-rhenium alloy, which has bend ductile-brittle transition temperatures less than -195° C (less than -320° F) and -130° C (-200° F) in the worked and recrystallized conditions, respectively, compared with an average of 0° C (30° F) and 65° C (150° F) for unalloyed molybdenum.

2. Rhenium promotes normal solid solution strengthening in molybdenum at elevated temperatures. At 1315° C (2400° F), the molybdenum - 5.9-rhenium alloy has a 70 percent greater tensile strength and a 100 percent greater creep strength than does the unalloyed molybdenum.

3. Rhenium additions increase the recrystallization temperature and decrease the annealed grain sizes in molybdenum.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, March 28, 1972,
114-03.

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TABLE I. - FABRICATION SCHEDULES FOR MOLYBDENUM AND MOLYBDENUM-RHENIUM ALLOYS

Rhenium content, at.%	0	3.9	5.9	7.7
Extrusion				
Temperature, °C (°F)	1425 (2600)	1540 (2800)	1455 (2650)	1455 (2650)
Reduction ratio	8	8	6	6
Swaging				
Temperature, °C	1095 to 815	------------	1175 to 925	1175 to 925
(°F)	(2000 to 1500)	------------	(2150 to 1700)	(2150 to 1700)
Final diameter, cm (in.)	0.66 (0.26)	------------	0.66 (0.26)	0.66 (0.26)
Reduction, percent	89	------------	91	91
Rolling				
Temperature, °C	1175 to 815	1125 to 955	1150 to 925	1150 to 925
(°F)	(2150 to 1500)	(2060 to 1750)	(2100 to 1700)	(2100 to 1700)
Final thickness, cm (in.)	0.084 (0.033)	0.089 (0.035)	0.102 (0.040)	0.102 (0.040)
Reduction, percent	92	81	95	95

TABLE II. - ANALYSES OF MOLYBDENUM AND MOLYBDENUM-RHENIUM ALLOYS

Rhenium, at.%	0	3.9	5.9	7.7
Oxygen, ppm	12	11	35	27
Nitrogen, ppm	5	15	6	2
Carbon, ppm	15	5	37	23

TABLE III. - BEND TRANSITION TEMPERATURES

Rhenium content, at.%	1-Hour annealing temperature, °C	1-Hour annealing temperature, °F	Approximate bend transition temperature, °C	Approximate bend transition temperature, °F	Grain or subgrain size, μm
0	(a)	----	5	40	[b]1.9
	480	900	≤25	≤75	[b]2.1
	1095	2000	50	125	58
	1260	2300	65	150	64
	(c)	----	-60	-75	[b]1.2
	480	900	-75	-100	[b]1.6
	1260	2300	65	150	49
3.9	(d)	----	-155	-250	[b]1.6
	925	1700	-195	-320	[b]2.6
	1260	2300	-45	-50	----
	1370	2500	25	75	38
5.9	(d)	----	<-195	<-320	[b]2.1
	925	1700	<-195	<-320	[b]2.9
	1370	2500	-85	-125	38
7.7	(d)	----	<-195	<-320	[b]1.7
	925	1700	<-195	<-320	[b]1.7
	1370	2500	-130	-200	24

[a]Rolled at 1175° to 815° C (2150° to 1500° F); not annealed.
[b]Subgrain size.
[c]Rolled at 1175° to 925° C (2150° to 1700° F); not annealed.
[d]As rolled; not annealed.

TABLE IV. - LOW-TEMPERATURE TENSILE PROPERTIES

1-Hour annealing temperature		Test temperature		0.2-Percent offset yield strength		Ultimate strength		Elongation, percent	Reduction in area, percent	Grain or subgrain size, μm	Approximate ductile-brittle transition temperature	
°C	°F	°C	°F	MN/m^2	ksi	MN/m^2	ksi				°C	°F
100 Mo, sheet												
(a)	----	25	75	----	------	261	37.8	0	--	-----	>25	>75
100 Mo, rod												
(b)	----	25	75	607	88.1	639	92.7	32	63	-----	<25	<75
1315	2400	-20	0	----	------	321	46.6	2	0	95	65	150
		25	75	265	38.4	411	59.6	4	3	-----		
		65	150	222	32.2	361	52.4	10	5	-----		
		125	260	121	17.6	282	40.9	55	77	-----		
		225	440	108	15.6	242	35.1	55	86	-----		
Mo - 3.9 Re, sheet												
(a)	----	25	75	752	109	820	119	6	--	-----	<25	<75
		25	75	779	113	779	116	8	--	-----		
Mo - 5.9 Re, rod												
(b)	----	-185	-300	1179	171	1248	181	5	3	[c]1.0	-180	-290
		-130	-200	1048	152	1179	171	17	34	-----		
		-75	-100	869	126	1000	145	20	46	-----		
		25	75	703	102	800	116	18	60	-----		
1425	2600	-195	-320	----	------	855	124	0	0	60	-100	-150
		-125	-190	619	89.8	676	98.1	4	3	-----		
		-75	-100	436	[d]63.2	543	78.9	6	9	-----		
		-40	-44	350	[d]50.8	589	85.4	34	29	-----		
		-20	0	296	[d]42.9	550	79.8	14	12	-----		
		5	40	294	[d]42.6	581	84.2	23	18	-----		
		25	75	262	[d]38.0	504	73.1	38	49	-----		
		190	370	182	[d]26.4	374	54.2	34	82	-----		
		305	580	161	23.4	349	50.6	37	81	-----		
Mo - 7.7 Re, rod												
(b)	----	-130	-200	1034	150	1213	176	13	10	-----	<-130	<-200
		-75	-100	945	137	1076	156	19	34	[c]0.95		
		-20	0	800	116	896	130	15	49	-----		
		25	75	848	123	896	130	13	50	-----		
		95	200	779	113	807	117	10	70	-----		
1425	2600	-195	-320	793	[d]115	807	117	1	3	62	-165	-270
		-125	-190	525	[d]76.1	724	105	15	10	-----		
		-75	-100	445	[d]64.6	605	87.8	12	13	-----		
		-40	-44	368	[d]53.4	620	89.9	34	29	-----		
		-20	0	367	[d]53.3	610	88.4	26	22	-----		
		5	40	312	[d]45.3	544	78.9	17	54	-----		
		25	75	311	[d]45.1	520	75.7	43	49	-----		
		25	75	317	[d]46.0	538	78.1	34	49	-----		
		190	370	222	[d]32.2	422	61.2	42	78	-----		
		305	580	196	28.4	361	52.3	30	79	-----		

[a]As rolled; not annealed.
[b]As swaged; not annealed.
[c]Subgrain width.
[d]Lower yield point.

TABLE V. - HIGH-TEMPERATURE TENSILE PROPERTIES

1-Hour annealing temperature		Test temperature		0.2-Percent offset yield strength		Ultimate strength		Elongation, percent	Reduction in area, percent	Final grain size, μm
°C	°F	°C	°F	MN/m²	ksi	MN/m²	ksi			
100 Mo, sheet										
(a)	----	980	1800	40.9	5.93	105	15.3	51	---	81
		1205	2200	29.0	4.20	71.7	10.4	(b)	---	---
		1205	2200	22.4	3.25	73.8	10.7	50	---	149
		1425	2600	16.8	2.44	46.9	6.80	26	---	166
1315	2400	980	1800	35.8	5.19	106	15.4	60	---	86
		1205	2200	23.2	3.36	72.4	10.5	53	---	---
		1205	2200	23.4	3.39	71.7	10.4	46	---	65
		1425	2600	16.1	2.33	48.3	7.0	69	---	144
100 Mo, rod										
(c)	----	980	1800	100	14.5	116	16.8	50	>95	(d)
		1315	2400	25.7	3.73	58.3	8.45	65	>95	119
		1650	3000	14.3	2.07	29.9	4.34	49	>95	---
1315	2400	980	1800	51.0	7.39	105	15.2	62	93	91
		1315	2400	25.1	3.64	56.3	8.16	78	>95	98
Mo - 3.9 Re, sheet										
(a)	----	980	1800	310	44.9	36.0	52.2	6	---	---
		1315	2400	75.8	11.0	94.5	13.7	41	---	---
		1425	2600	28.3	4.10	59.6	8.64	63	---	---
		1650	3000	19.7	2.85	42.1	6.10	65	---	65
1315	2400	980	1800	50.5	7.33	161	23.3	45	---	---
		1205	2200	44.7	6.48	94.5	13.7	49	---	---
		1425	2600	24.9	3.61	60.1	8.72	58	---	---
Mo - 5.9 Re, rod										
(c)	----	980	1800	38.0	55.1	400	58.0	10	79	---
		1315	2400	79.3	11.5	101	14.6	38	>95	21
		1650	3000	24.8	3.59	45.9	6.66	66	>95	58
1425	2600	980	1800	260	37.7	268	38.8	19	>95	30
		1315	2400	77.2	11.2	95.1	13.8	53	>95	---
		1650	3000	24.3	3.52	43.4	6.30	51	>95	64
Mo - 7.7 Re, rod										
(c)	----	980	1800	44.3	64.3	467	67.7	14	86	---
		1315	2400	59.3	8.60	98.6	14.3	60	>95	26
		1650	3000	25.4	3.68	46.5	6.74	77	>95	79
1425	2600	980	1800	130	18.8	197	28.6	44	90	75
		1315	2400	57.0	8.27	102	14.8	56	>95	48
		1650	3000	26.2	3.80	46.2	6.70	78	>95	69

[a]As rolled; not annealed.
[b]Broke in grip.
[c]As swaged; not annealed.
[d]Partially wrought structure.

TABLE VI. - CREEP DATA

Condition	Test temperature		Stress		Steady creep rate, sec^{-1}	Stress dependency, n	Rupture life, hr	Final grain size, μm
	^{o}C	^{o}F	MN/m^2	ksi				
100 Mo								
As rolled	1205	2200	23.0	3.34	0.22×10^{-6}			
			23.7	3.94	.57			
			33.4	4.85	2.9			
			39.7	5.76	6.1			
			48.1	6.97	24	6.2	------	82
As rolled	1425	2600	14.4	2.09	0.21×10^{-6}			
			17.5	2.54	.31			
			21.6	3.13	2.3			
			25.7	3.73	8.1			
			30.9	4.48	32	6.8	------	310
As rolled	1425	2600	35.2	5.10	83×10^{-6}	---	0.56	82
As swaged	1315	2400	13.8	2.0	0.086×10^{-6}			
			17.2	2.5	.21			
			20.7	3.0	.66			
			24.1	3.5	1.3			
			27.6	4.0	1.8			
			31.0	4.5	4.4	4.8	------	160
As swaged	1315	2400	13.8	2.0	0.13×10^{-6}	---	736	---
Mo - 3.9 Re								
As rolled	980	1800	47.4	6.88	0.03×10^{-6}			
			66.8	9.69	.09			
			80.7	11.7	.37			
			134	19.4	1.2	3.5	------	(a)
As rolled	1315	2400	25.0	3.62	0.40×10^{-6}			
			33.9	4.92	1.5			
			39.3	5.70	3.2			
			44.6	6.47	6.8			
			51.7	7.50	18	5.0	------	38
As rolled	1315	2400	41.9	6.08	4.8×10^{-6}	---	20.5	35
As rolled	1425	2600	18.5	2.69	0.36×10^{-6}			
			22.6	3.28	1.0			
			26.8	3.88	2.8			
			30.9	4.48	5.6			
			35.0	5.07	13	5.5	------	45
As rolled	1650	3000	14.8	2.14	3.0×10^{-6}			
			18.5	2.68	7.8			
			22.1	3.21	18			
			25.8	3.74	61	5.1	------	230

[a]Worked microstructure.

TABLE VI. - Concluded. CREEP DATA

Condition	Test temperature		Stress		Steady creep rate, sec^{-1}	Stress dependency, n	Rupture life, hr	Final grain size, μm
	°C	°F	MN/m^2	ksi				
Mo - 5.9 Re								
As swaged	980	1800	138	20.0	0.024×10^{-6}			
			165	24.0	.068			
			221	32.0	.49	6.5	-----	---
As swaged	1315	2400	34.5	5.0	0.083×10^{-6}			
			41.4	6.0	.15			
			55.2	8.0	1.2			
			68.9	10.0	6.7			
			82.7	12.0	60	7.5	-----	80
As swaged	1315	2400	34.5	5.0	0.11×10^{-6}	---	157	---
As swaged	1315	2400	41.4	6.0	1.0×10^{-6}	---	36.6	---
As swaged	1315	2400	55.2	8.0	3.0×10^{-6}	---	7.6	---
Annealed[b]	1315	2400	34.5	5.0	0.18×10^{-6}			
			41.4	6.0	.39			
			48.3	7.0	1.7			
			55.2	8.0	4.1			
			62.1	9.0	11			
			68.9	10.0	19	7.1	-----	58
As swaged	1650	3000	13.8	2.0	0.11×10^{-6}			
			20.7	3.0	1.2			
			27.6	4.0	8.1			
			34.5	5.0	42	6.5	-----	330
Mo - 7.7 Re								
As swaged	980	1800	152	22.0	0.028×10^{-6}			
			193	28.0	.076			
			248	36.0	.65	6.4	-----	---
As swaged	1315	2400	41.4	6.0	0.49×10^{-6}			
			48.3	7.0	1.6			
			55.2	8.0	3.7			
			68.9	10.0	22			
			82.7	12.0	160	8.2	-----	46
As swaged	1315	2400	34.5	5.0	0.22×10^{-6}	---	263	77
As swaged	1315	2400	41.4	6.0	1.2×10^{-6}	---	90.3	62
As swaged	1315	2400	48.3	7.0	5.6×10^{-6}	---	12.3	49
As swaged	1315	2400	55.2	8.0	5.8×10^{-6}	---	11.9	---
Annealed[b]	1315	2400	27.6	4.0	0.069×10^{-6}			
			41.4	6.0	.68			
			55.2	8.0	4.7			
			68.9	10.0	15	6.0	-----	54
As swaged	1650	3000	17.2	2.5	1.3×10^{-6}			
			20.7	3.0	3.8			
			24.1	3.5	8.3			
			27.6	4.0	22			
			31.0	4.5	57	6.3	-----	300

[b]Annealed 1 hour at 1425° C (2600° F).

TABLE VII. - ANNEALING DATA

1-Hour annealing temperature, °C	1-Hour annealing temperature, °F	Fraction recrystal-lized	Grain size, μm	Diamond pyramid hardness, kg/mm^2	Recrystallization temperature, °C	Recrystallization temperature, °F
			100 Mo			
(a)	----	0	---	241		
540	1000	0	---	243		
595	1100	0.25	---	264		
650	1200	.90	---	201		
760	1400	.92	---	183		
870	1600	.98	---	181		
980	1800	1.0	36	177		
1095	2000	1.0	32	---		
1205	2200	1.0	41	---		
1315	2400	1.0	54	---		
1425	2600	1.0	67	173		
1540	2800	1.0	58	---		
1650	3000	1.0	79	---		
1720	3125	1.0	74	---	925	1700
			Mo - 3.9 Re			
(b)	----	0	---	272		
760	1400	0	---	268		
815	1500	0	---	258		
870	1600	0	---	230		
925	1700	0	---	236		
980	1800	0	---	225		
1040	1900	0.01	---	227		
1095	2000	<.01	---	228		
1150	2100	.10	---	224		
1205	2200	.90	27	159		
1315	2400	1.0	30	151		
1425	2600	1.0	31	146		
1540	2800	1.0	35	---		
1650	3000	1.0	45	---		
1720	3125	1.0	57	---		
1760	3200	1.0	59	---		
1870	3400	1.0	121	---		
1980	3600	1.0	515	---	1260	2300
			Mo - 5.9 Re			
(c)	----	0	---	276		
1095	2000	0	---	240		
1205	2200	0.40	---	215		
1315	2400	.99	39	165		
1425	2600	1.0	37	169		
1540	2800	1.0	40	---		
1650	3000	1.0	80	---		
1760	3200	1.0	102	157	1370	2500
			Mo - 7.7 Re			
(c)	----	0	---	299		
1095	2000	0	---	251		
1205	2200	0.10	---	232		
1315	2400	.98	21	179		
1425	2600	1.0	27	183		
1540	2800	1.0	29	187		
1650	3000	1.0	76	173		
1760	3200	1.0	92	170	1370	2500

[a]As rolled 92 percent; not annealed.
[b]As rolled 81 percent; not annealed.
[c]As swaged 91 percent; not annealed.