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TENSILE PROPERTIES OF MOLYBDENUM AND TUNGSTEN

FROM 2500° TO 3700° F

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SUMMARY

Specimens of commercially pure sintered tungsten, arc-cast unalloyed molybdenum, and two arc-cast molybdenum-base alloys (one with 0.5 percent titanium, the other with 0.46 percent titanium and 0.07 percent zirconium) were fabricated from 1/2-inch-diameter rolled or swaged bars. All specimens were evaluated in short-time tensile tests in the as-received condition, and all except the molybdenum-titanium-zirconium alloy were tested after a 30-minute recrystallization anneal at 3800° F in a vacuum of approximately 0.1 micron.

Results showed that the tungsten was considerably stronger than either the arc-cast unalloyed molybdenum or the molybdenum-base alloys over the 2500° to 3700° F temperature range. Recrystallization of swaged tungsten at 3800° F considerably reduced its tensile strength at 2500° F. However, above 3100° F, the as-swaged tungsten specimens recrystallized during testing, and had about the same strength as when recrystallized at 3800° F before evaluation. The ductility of molybdenum-base materials was very high at all test temperatures; the ductility of tungsten decreased sharply above about 3120° F.

INTRODUCTION

Modern high-speed aircraft and missiles require materials capable of operating at very high temperatures. Since the service temperatures often exceed the melting points of current "superalloys," metals with much higher melting points must be considered. For those applications where oxidation resistance is not essential, the refractory metals tungsten (m.p., 6170° F) and molybdenum (m.p., 4760° F) possess outstanding potential.

Although these metals and their alloys are potentially useful as structural materials for very high temperature service, little information is available on their strength above 2500° F. This scarcity of information is due in part to the lack of testing equipment capable of evaluating materials at very high temperatures. Equipment designed to evaluate the tensile properties of materials in the temperature range 2500° to 4000° F has been developed at the NASA Lewis Research Center. This report describes the equipment and presents the results of a preliminary investigation of the tensile properties of wrought sintered tungsten, arc-cast unalloyed molybdenum, and a commercial arc-cast molybdenum alloy containing 0.5 percent titanium. The results of two tests of an experimental arc-cast molybdenum alloy containing 0.46 percent titanium and 0.07 percent zirconium are also included.

Available data in the literature on the tensile properties of unalloyed molybdenum and tungsten at temperatures above 2500° F are reported in references 1 to 6. No previous data on the tensile properties of molybdenum alloys above 2500° F was found.

In most of the previous investigations of tensile properties of molybdenum and tungsten at very high temperatures, long thin test specimens such as wires or sheets were used. Because of the influence of fabrication history and the presence of highly oriented grain structures, the properties reported for these thin wires or sheets may not be representative of the properties of less severely worked material. In this investigation, specimens with a 1/4-inch test section were fabricated from 1/2-inch-diameter rolled or swaged bars and were evaluated in short-time tensile tests at 2500° to 3700° F.

MATERIALS, APPARATUS, AND PROCEDURE

Materials

The materials evaluated were arc-cast unalloyed molybdenum, two arc-cast molybdenum-base alloys, and commercially pure sintered tungsten. The molybdenum-base materials were produced and fabricated by the Climax Molybdenum Company of Michigan, and the tungsten by Cleveland Tungsten, Inc. Chemical composition of the molybdenum-base materials was reported by the manufacturer to be as follows:

Material	Composition, percent by weight		
	Carbon	Titanium	Zirconium
Unalloyed molybdenum	0.036	-----	-----
Commercial molybdenum alloy	.026	0.47	-----
Experimental molybdenum alloy	.017	.46	0.074

Chemical analysis of the tungsten indicated the following major impurities:

Element	Fe	Mo	Cr	Si	C	O	N	H
Composition, parts/million	210	180	40	30	4	25	15	1

Information supplied by the manufacturer on the processing history of the materials is given in the appendix.

The materials were received as 1/2-inch-diameter rolled or swaged rods and were evaluated in the as-received condition. In addition, specimens of all materials except the experimental molybdenum alloy were evaluated after a 30-minute recrystallization anneal at 3800° F in a vacuum of approximately 0.1 micron. A recrystallization temperature slightly above the maximum evaluation temperature was selected in order to stabilize the grain size of the bars during the heating and testing period. Photomicrographs of the as-received and recrystallized bars are shown in figure 1.

Apparatus and Procedure

The tensile-test apparatus used in this investigation was developed for the purpose of testing metals, cermets, and ceramics at temperatures above 2500° F. Consequently, some features of the design were chosen to permit the evaluation of brittle nonconducting materials that are available only in relatively short lengths and in experimental quantities. Figure 2 is a photograph of the equipment.

Tensile-testing machine. - A commercial, screw-driven, tensile-testing machine with a low scale of 1500-pound-load capacity was used. The crosshead speed was continuously variable from about 0.005 inch per minute to 2 inches per minute by means of a variable-speed motor equipped with thyratron speed control.

Vacuum test chamber. - All tests were conducted in a vacuum of 0.5 to 2.0 microns. The vacuum chamber, shown in figure 3, is a double-walled stainless-steel cylinder, 12 inches in diameter by 18 inches high, of welded construction. The ends and sides of the chamber are water-cooled. Flanged openings are provided at the front of the tank for pumping and at the rear for introduction of electrical leads for the induction coil. A pyrex window in the front cover is provided for observation of the specimen and grips, and for temperature checks with an optical pyrometer.

Pull rods enter the top and bottom of the test chamber through 3-inch-long sleeves welded to the end plates. Vacuum seals for the pull rods are made by neoprene O-rings seated in grooves in the pull rods. The O-rings are lubricated with vacuum grease and are compressed only enough to provide a reliable vacuum seal. Measurements indicated that the force required to overcome friction in the O-ring seals was 2 to 3 pounds.

The top of the chamber also contains two small flanged openings that are used for observation and for introducing thermocouples into the chamber.

Vacuum system. - The chamber is evacuated by a water-cooled, three-stage oil diffusion pump having a maximum pumping speed of 700 liters per second. This is backed by a single-stage mechanical forepump rated at 27 cubic feet per minute (12 liters/sec). Water-cooled baffles between the oil diffusion pump and test chamber minimize back-diffusion of oil vapors to the chamber. Pressure is measured with a cold-cathode ionization gage.

At room temperature, the vacuum chamber can be maintained at approximately 0.01 micron. However, during heating to the test temperature, outgassing of the specimen and heater causes the pressure to rise, the maximum pressure depending on the rate of heating. Since the induction coil used for heating is located inside the vacuum chamber, it is necessary to keep the pressure below the glow discharge range. Specimens were therefore heated at such a rate that the pressure in the chamber never exceeded 2 microns. In most tests, maximum pressure was limited to approximately 0.5 micron.

Heater assembly. - Figure 4 shows details of the heater assembly. The susceptor is a 1.5-inch-long seamless tantalum tube having an inner diameter of 3/4 inch and a wall thickness of 0.020 inch. It is inductively heated by a concentric water-cooled induction coil composed of six turns of 1/4-inch-diameter copper tubing. The induction coil is approximately $2\frac{1}{2}$ inches long and has an inner diameter of $1\frac{1}{4}$ inches. A high-purity (99.7 percent Al_2O_3) recrystallized alumina tube cemented to the inner surface of the induction coil with alumina cement provides both electrical and thermal insulation between the tantalum heater and the induction coil. A 0.010-inch-thick molybdenum radiation shield placed between, and concentric with, the tantalum and alumina tubes minimizes radiation losses from the heater and prevents overheating of the alumina tube. This radiation shield contains a longitudinal gap to minimize inductive heating of the shield. The tantalum susceptor is positioned by 0.020-inch-diameter tantalum wires as shown in figure 4.

Power supply. - The induction unit used with this equipment was a 15-kilowatt electronic tube generator with a frequency of approximately

375,000 cycles per second. The output of this generator was supplied to a 20-to-1 radio frequency output transformer in order to step down the voltage on the work coil and thus minimize arcing inside the vacuum chamber. Water-cooled copper leads approximately 15 inches long with a rectangular cross section 3/4-by-1/2 inch enter the vacuum chamber through a 1-inch-thick Mycalex plate. Vacuum seals are made by a neoprene O-ring and a Teflon gasket.

Tensile specimen, grips, and loading fixtures. - The design of the test specimen, grips, and loading fixtures used in this investigation was dictated by the fact that the equipment was designed primarily for testing brittle materials at very high temperatures. The testing of brittle materials requires that some means of assuring good axial alinement of specimens and pull rods be provided, for the presence of bending stresses leads to premature failure. In order to meet this requirement, the axial loading fixtures described in reference 7 and shown in figure 5 were used. With these axial loading fixtures, the load is applied through two balls accurately positioned in line with the axes of the loading rods. The specimen is attached to the loading rods by means of a precision fastening device. By holding close tolerances in the machining of the fixtures and test specimen, alinement is built into the fixtures and specimen assembly. Any factors tending to produce eccentricity external to the assembly are compensated for by low friction loading through the balls.

The test specimens used in this study are shown in figure 6. Buttonhead specimens were chosen because this type of fastening has been shown to provide superior alinement (ref. 7). The 5-inch length was selected because it could conveniently be obtained from experimental materials. Three slightly different type specimens were used at various stages of development of the program. The design labeled type a in figure 6 was that selected initially. It later appeared desirable to confine the gage length to that part of the specimen within the heater, and type b specimens were prepared. These specimens had a large radius at the ends of the test section in order to minimize stress concentrations when testing brittle materials. It was later decided that the large radii were unnecessary for the ductile materials being evaluated in this study, and type c specimens were adopted. These were easier to fabricate and had the advantage that the gage length was more sharply defined. Comparison of the data from tests using these different types of specimens indicated that the tensile strengths do not appear to be influenced by the type specimen used herein.

Since considerable care was used to incorporate accurate alinement into the loading fixtures by holding close machining tolerances, it was necessary to assure that the grips did not deform during the high-temperature tests. By gripping outside the heater assembly and providing molybdenum radiation shields between the heater and grips, a temperature of 3700° F was achieved at the center of the test specimen while the temperature of the Inconel-X grips was kept below 1500° F. For higher test temperatures, molybdenum-alloy grips are available.

With the arrangement of test specimen and heater described, there is a large temperature gradient along the longitudinal axis of the specimen. For example, at a test temperature of 3600° F, the temperature gradient along the central inch is approximately 150° F. The central 1/4 inch is at a relatively uniform temperature, however, the gradient across it being approximately 20° F. At lower test temperatures, the gradient is less severe. Thus, at 2500° F, the temperature gradient along the central inch is approximately 70° F. All failures occurred in the central part of the specimen, where the temperature was measured. It is believed that the reported tensile strengths and values of reduction of area at fracture are not greatly affected by the presence of the temperature gradient.

Temperature measurement and control. - Specimen temperature was measured with a tungsten-molybdenum thermocouple spot-welded to the surface of the specimen at its midpoint. Thermocouples made from 0.015-inch-diameter wires were calibrated by comparison with platinum-platinum, 13-percent rhodium thermocouples up to 3000° F and at the melting points of platinum (3216° F) and rhodium (3560° F). The latter calibrations were accomplished by using a platinum or rhodium wire as a fusible link across the thermocouple junction.

Temperature of the tantalum heater was controlled manually by varying the power to the oscillator tubes of the induction heater. For the short-time tensile tests reported herein, measured specimen temperature did not vary more than ±20° F during the course of the test.

Test procedure. - After the tensile specimen was positioned in the grips and the test chamber was evacuated to 0.01 to 0.05 micron of mercury, the specimen was slowly brought to the test temperature. The heating rate was determined by the rate of outgassing of the specimen and heater assembly and was such that pressure in the chamber never exceeded 2 microns. For a 3600° F test, heating time was approximately 1 hour. The specimen was held 15 minutes at temperature and was then loaded to fracture at a crosshead speed of 1/16 inch per minute.

RESULTS AND DISCUSSION

Effect of Temperature on Tensile Strength of As-Received Materials

The results of high-temperature tensile tests of as-received materials are presented in table I and in figure 7. The superior strength of tungsten over the molybdenum-base materials is apparent. Part of this superiority is due to the retention of cold work to higher temperatures because of the higher recrystallization temperature of tungsten. Even at the lowest test temperature (2500° F), the molybdenum-base materials were partially or completely recrystallized during test. In contrast, tungsten was only partially recrystallized during testing at 3120° F.

Figure 7 also shows that the strength advantage of the molybdenum alloys over unalloyed molybdenum decreases rapidly with increasing temperature. Reference 8 reports a tensile strength at 1600° F of 86,900 psi for an 0.45-percent-titanium alloy, compared with 52,000 psi for unalloyed molybdenum. At 2500° F, the data reported herein show that the strength advantage of the 0.5-percent-titanium alloy is only about 7000 psi (22,500 psi for the alloy, compared with 15,290 psi for unalloyed molybdenum). At 3600° F, unalloyed molybdenum and the 0.5-percent-titanium alloy have about the same tensile strength, approximately 2200 psi.

On the basis of the two tests conducted, the experimental molybdenum alloy containing 0.5 percent titanium and 0.07 percent zirconium is stronger at high temperatures than the molybdenum alloy containing only 0.5 percent titanium.

The mechanism by which small amounts of titanium and zirconium exert relatively large influence on the strength of molybdenum is not well understood and is currently the subject of investigation elsewhere (ref. 9). Metallographic examination of fractured specimens showed that one effect of the alloying elements was to raise the recrystallization temperature and also to inhibit grain growth above the recrystallization temperature. Figure 8 shows the microstructures of as-received unalloyed molybdenum and the molybdenum alloy containing 0.5 percent titanium after test at 3500° F. The grain size of the unalloyed molybdenum is much larger, and there are numerous coarse carbides both at the grain boundaries and within the grains. On the other hand, the titanium-bearing alloy has a smaller grain size and shows a cellular structure within the grains. Examination at higher magnification (fig. 8(b)) revealed the presence of a very fine precipitate at the cell boundaries.

Effect of Temperature on Tensile Strength of Recrystallized Materials

Tensile strengths of the materials evaluated after recrystallization at 3800° F are listed in table II and are plotted as a function of temperature in figure 9. Comparison of the strengths of the materials in the as-worked and recrystallized conditions (fig. 10) indicates the following:

(1) At 2500° F, tungsten that has been recrystallized at 3800° F is much weaker than it is in the as-swaged condition. However, above 3100° F, there is little difference in the strengths of the recrystallized and as-swaged materials. This is not surprising, since the as-swaged tungsten recrystallizes during testing at temperatures above about 3100° F and thus loses the strengthening effects of cold work. Since the grain size of the as-received and recrystallized materials was very similar, no effects of grain size on strength could be expected in these tests.

(2) The molybdenum-base materials exhibited relatively small strength differences between the recrystallized and as-received specimens. Since, as noted previously, the molybdenum-base materials undergo recrystallization even at the lowest test temperature, strength differences due to cold working would not be expected. However, strength differences due to differences in grain size and in carbide shape and distribution might be anticipated. The 3800° F recrystallized material had a very large grain size (ASTM 1 or larger), while the grain size observed in the as-received material after testing was much smaller at the lower end of the test temperature range and increased with increasing test temperature. Since only small differences were observed between the strengths of the recrystallized and as-received materials, it can be concluded that grain size has little effect on the tensile strengths of molybdenum and the molybdenum plus 0.5 percent titanium alloy at temperatures near 2500° F.

Comparison of Fracture Ductilities of Tungsten and Molybdenum-Base Materials

Total elongation and reduction of area at fracture for both as-received and recrystallized specimens are listed in tables I and II. For specimen types a and b (fig. 6), in which the gage length was not well defined, total elongation was measured between the inner surfaces of the buttonheads. For type c, elongation was measured between punch marks on the shoulders of the specimen just above the fillets of the reduced section. In the latter case, percentage elongations were calculated, with a gage length of 1 inch assumed. This assumption neglects the effect of the temperature gradient, which produces an effective gage length somewhat less than 1 inch. Thus, the percent elongation data reported are somewhat lower than would be expected if no temperature gradient existed along the gage length.

The molybdenum-base materials exhibited high ductility throughout the entire temperature range, both in the as-received and recrystallized conditions. Localized necking down at the fracture zone always preceded fracture. As shown in figure 11(a), the appearance of the necked region changed with temperature as a result of grain coarsening at high test temperatures. Metallographic examination of molybdenum-base materials fractured at 3500° F or above showed either single crystals or several very large grains in the fracture region. Figure 11(b) shows two views of the wedge-type fracture of a recrystallized molybdenum plus 0.5 percent titanium alloy specimen evaluated at 3600° F.

In contrast to the uniformly high ductilities of the molybdenum-base materials, both as-swaged and recrystallized tungsten exhibited a substantial decrease in ductility with increasing temperature. Figure 12 shows the change in character of fracture of as-received tungsten over the range 2500° to 3500° F. At temperatures above 3120° F specimens failed without appreciable necking down, giving the fracture a brittle appearance. However, measurements of elongation and reduction of area indicated that a considerable amount of plastic flow preceded fracture. Metallographic examination indicated that fractures were intergranular in this temperature range of reduced ductility; at lower temperatures, the fractures were either transgranular or partially transgranular and intergranular.

Metallographic Observation of Carbide Plasticity in Molybdenum

The series of photomicrographs shown in figure 13 demonstrate the plasticity of molybdenum carbide in unalloyed molybdenum at elevated temperatures. Slight elongation of the carbides in the as-rolled material suggests that the carbide had been plastically deformed in the working process. During tensile testing at 3230° F, the carbides in unalloyed molybdenum were severely deformed into long stringers, as shown in figure 13(b). After testing at 3460° F the elongated carbides were no longer observed. Instead, carbides were present primarily as fine matrix and grain boundary precipitates. Occasionally chains of angular carbides were observed (fig. 13(c)). Apparently the original carbides were taken into solution during the 3460° F test and were later reprecipitated.

Comparison of Tensile Strengths of Tungsten with Data from Previous Investigations

Tensile strengths of tungsten determined in this investigation are compared with data from previous investigations in figure 14. The data of reference 5 are for recrystallized tungsten, but the size of the material evaluated is not reported. Reference 4 gives data for wrought 0.024-inch-diameter wire. There is a wide spread in the reported strengths even at temperatures above 3000° F, where the effects of cold working should be largely eliminated by annealing. Evidently such variables as fabrication history, specimen size, chemical composition, and grain size and shape exert considerable influence on the strength of tungsten at high temperatures.

SUMMARY OF RESULTS

The following results were obtained from an investigation of the high-temperature tensile properties of sintered tungsten, arc-cast unalloyed molybdenum, and two arc-cast molybdenum-base alloys:

1. In the temperature range 2500° to 3700° F, commercially pure tungsten was considerably stronger than arc-cast unalloyed molybdenum or the molybdenum alloy containing 0.5 percent titanium. For example, at 2500° F, the tensile strength of as-swaged tungsten was approximately 49,000 psi, that of the as-swaged molybdenum plus 0.5 percent titanium alloy was 22,000, and that of the as-rolled unalloyed molybdenum was 15,000 psi. At 3600° F, tungsten had a tensile strength of about 10,000 psi, while unalloyed molybdenum and the molybdenum plus 0.5 percent titanium alloy both had strengths of approximately 2200 psi. Two tests of an experimental, arc-cast molybdenum alloy containing 0.46 percent titanium and 0.07 percent zirconium gave tensile strengths at 3000° and 3500° F of approximately 14,000 and 4200 psi, respectively. For the alloys evaluated, the strengthening effectiveness of the alloying elements added to arc-cast molybdenum decreased with increasing temperature.

2. Recrystallization at 3800° F reduced the tensile strength of tungsten at 2500° F from 49,000 psi to about 32,000 psi. Above 3100° F, the as-swaged tungsten recrystallized during testing and had approximately the same strength as that annealed at 3800° F prior to evaluation.

3. The ductility of the molybdenum-base materials was very high at all test temperatures. In contrast, the ductility of tungsten as measured by elongation and reduction of area at fracture decreased sharply at temperatures above about 3120° F. This decrease in ductility was associated with the onset of intergranular cracking.

CONCLUDING REMARKS

While tungsten and molybdenum-base materials are potentially useful as structural materials for ultra-high temperature applications, much remains to be accomplished before the full potentialities of these materials can be realized. At the present time, the commercially available, arc-cast molybdenum alloys are all of the solid-solution type and depend primarily on cold work for strengthening. Since the recrystallization temperatures for these alloys generally do not exceed 2600° F, the materials lose the effects of cold-work strengthening at temperatures below this and, as shown in this study, are little stronger than unalloyed molybdenum at higher temperatures. Stronger molybdenum alloys have been produced experimentally but cannot be readily worked with existing commercial facilities in which the working temperature is limited to about 2400° F. When facilities become available for true hot working of molybdenum-base materials, alloys with greater strengths at higher temperatures should become available.

While molybdenum-base alloys have been studied extensively in the last ten years, tungsten-base alloys have received very little attention. Tungsten's high ductile-to-brittle transition temperature, poor oxidation resistance, high density, poor fabricability and weldability, and the size limitations of the powder metallurgy process commonly used for its manufacture have made it relatively unattractive as a potential structural material for temperatures up to about 2500° F. For such temperatures, columbium and molybdenum-base materials appeared to pose fewer problems. The increasing need for materials to operate at temperatures above 3500° F has stimulated research on tungsten. The fact that even unalloyed tungsten is considerably stronger at very high temperatures than the strongest available molybdenum alloys is a compelling reason to explore fully the possibility of developing tungsten-base materials for ultra-high temperature applications.

Lewis Research Center
National Aeronautics and Space Administration
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APPENDIX - PROCESSING SCHEDULE OF MATERIALS EVALUATED

Tungsten

Information on the processing history of the bars of tungsten evaluated in this study was not available. However, the manufacturer supplied the following information on the normal processing schedule for bars of this type.

The pressed ingot was 1 by 1 by 24 inches. The pressed ingot was presintered in a hydrogen-atmosphere furnace, followed by a final sintering treatment at 3100° C in hydrogen. The ingot was reduced to 1/2-inch diameter by swaging at temperatures ranging from 1600° C at the initial swage to 1300° C at the finished size. An intermediate anneal was given at 0.800-inch diameter.

Molybdenum

Information supplied by the manufacturer on the processing schedule for the molybdenum-base materials is given in the following table:

Material	Diameter of arc-cast ingot, in.	Diameter of casting after machining, in.	Extrusion practice (a)	Diameter of machined extrusion, in.	Rolling history
Unalloyed molybdenum	8	7	Extruded to $3\frac{3}{4}$-inch diameter at 2300° F	$3\frac{11}{16}$	Rolled to 1/2-inch diameter at 2200° F.
Molybdenum + 0.5% titanium	$7\frac{1}{2}$	$6\frac{5}{8}$	Extruded to $4\frac{1}{4}$-inch diameter at 2325° F	$4\frac{1}{32}$	Rolled to 2-inch diameter at 2350° F. Rolled bar recrystallized. Recrystallized bar rolled to 15/16-inch diameter at 2350° F. Rolled bar fully recrystallized. Recrystallized bar rolled to 1/2-inch diameter at 2350° F.
Molybdenum + 0.5% titanium + 0.07% zirconium	$7\frac{1}{2}$	$6\frac{5}{8}$	Extruded to $4\frac{1}{4}$-inch diameter at 2450° F	$3\frac{7}{8}$	Rolled to 2-inch diameter at 2400° F. Rolled bar fully recrystallized. Recrystallized bar rolled to $1\frac{1}{4}$-inch diameter at 2400° F. Rolled bar fully recrystallized. Rolled bar swaged to 1/2-inch diameter at 2300° F.

[a]Bars were fully recrystallized following extrusion and then were machined and rolled.

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TABLE I. - SHORT-TIME TENSILE PROPERTIES OF AS-RECEIVED

TUNGSTEN, MOLYBDENUM, AND MOLYBDENUM ALLOYS

Temperature, °F	Specimen type (a)	Ultimate tensile strength, psi	Elongation between buttonheads, in.	Elongation in 1-inch reduced section, percent	Reduction of area, percent
Tungsten					
2500	a	49,350	0.62	--	95
[b]2750	↓	31,990	.20	--	47
3120	↓	15,220	.53	--	78
3500	↓	10,130	.25	--	34
3530	↓	11,500	.25	--	22
3630	↓	10,000	.19	--	28
Molybdenum					
2500	b	15,480	0.53	--	99
2500	c	15,100	.53	53	98
2750	c	10,470	.53	53	99
2920	b	7,960	.56	--	99
3000	c	6,680	.59	59	99
3230	b	4,600	.63	--	99
3300	c	3,760	.66	66	99
3460	b	2,780	.84	--	99
3500	c	2,890	.72	72	99
3700	c	1,880	.78	78	99
Molybdenum + 0.5 percent titanium					
2500	a	23,700	0.47	--	99
2500	c	21,300	.53	53	99
2750	c	14,650	.53	53	99
2890	a	11,100	.53	--	99
3000	c	9,800	.56	56	99
3260	a	5,540	.59	--	99
3300	c	5,270	.56	56	99
3350	a	3,980	.59	--	99
3500	a	2,680	.69	69	99
3500	c	3,380	.75	75	99
3700	c	1,800	.69	69	99
Molybdenum + 0.5 percent titanium + 0.07 percent zirconium					
3000	c	14,050	0.50	50	99
3510	c	4,180	.66	66	99

[a]Specimen types are shown in figure 6.

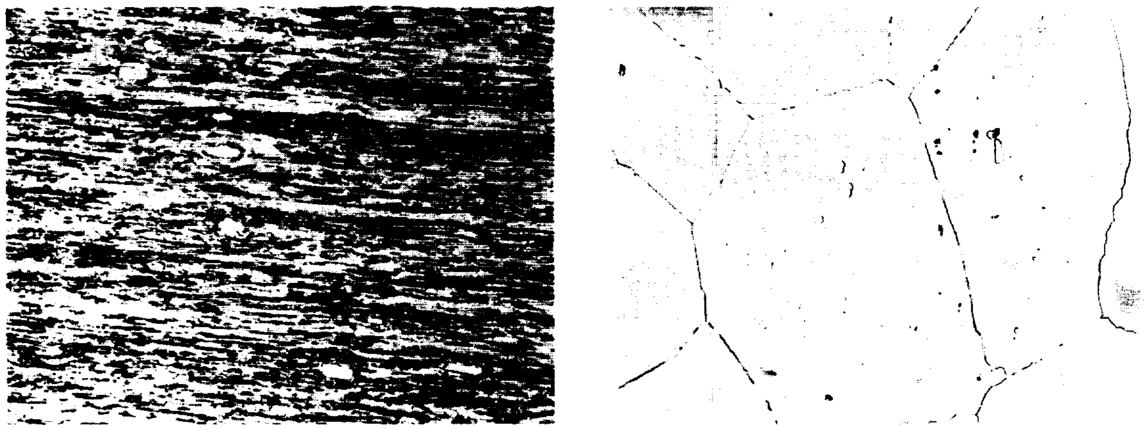
[b]Tensile properties, particularly ductility, may be in error for this test. In addition to usual fracture perpendicular to axis of applied stress, this specimen split along its centerline parallel to axis of applied stress.

TABLE II. - SHORT-TIME TENSILE PROPERTIES OF RECRYSTALLIZED[a] TUNGSTEN, MOLYBDENUM, AND MOLYBDENUM PLUS 0.5 PERCENT TITANIUM ALLOY

Temperature, °F	Specimen type (b)	Ultimate tensile strength, psi	Elongation between buttonheads, in.	Reduction of area, percent
Tungsten				
2500	a	31,910	0.62	95
3000	a	19,040	.63	75
3250	a	14,320	.27	36
3600	a	9,780	.20	25
Molybdenum				
2500	b	13,490	0.64	96
3000	b	5,900	.61	99
3600	b	2,135	.69	99
Molybdenum + 0.5 percent titanium				
2500	a	24,400	0.36	75
3000	a	8,400	.47	96
3250	a	4,150	.56	99
3600	a	1,265	.38	95

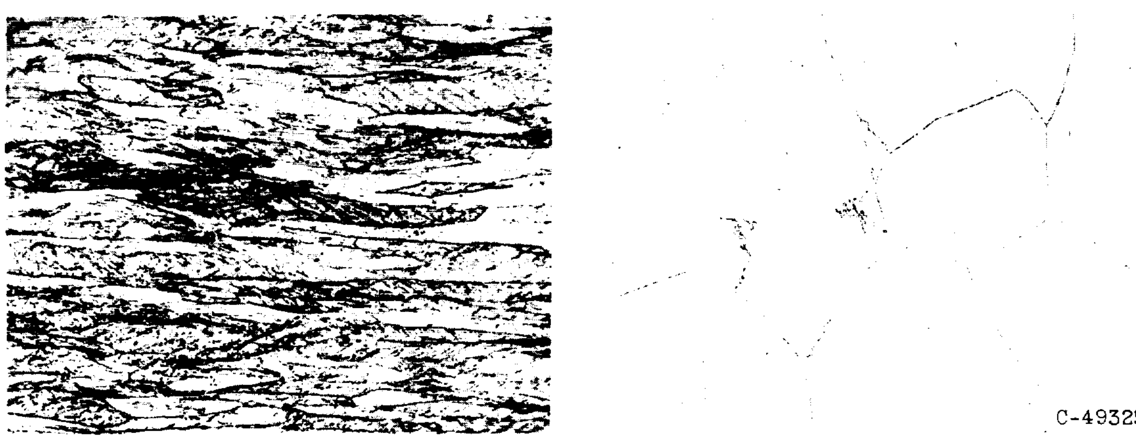
[a]Recrystallized at 3800° F for 1/2 hour in vacuum.

[b]Specimen types are shown in figure 6.



As received　　　　Recrystallized at 3800° F

(a) Arc-cast unalloyed molybdenum.



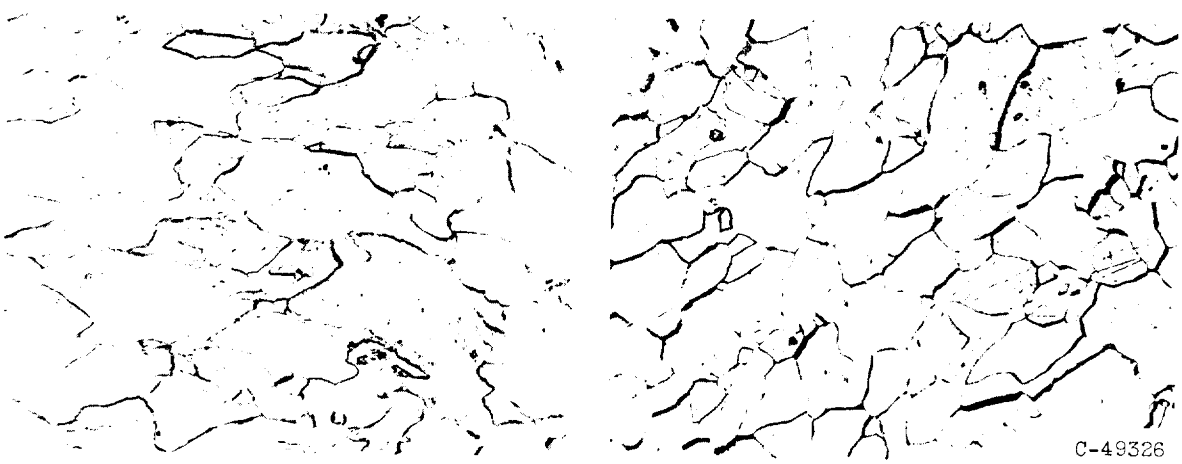
As received　　　　Recrystallized at 3800° F

(b) Arc-cast molybdenum plus 0.5 percent titanium.

Figure 1. - Microstructure of as-received and recrystallized molybdenum, molybdenum-base alloys, and tungsten. Longitudinal section; X250.

As received

(c) Arc-cast molybdenum plus 0.5 percent titanium and 0.07 percent zirconium.



As received

Recrystallized at 3800° F

(d) Sintered tungsten.

Figure 1. - Concluded. Microstructure of as-received and recrystallized molybdenum, molybdenum-base alloys, and tungsten. Longitudinal section; X250.

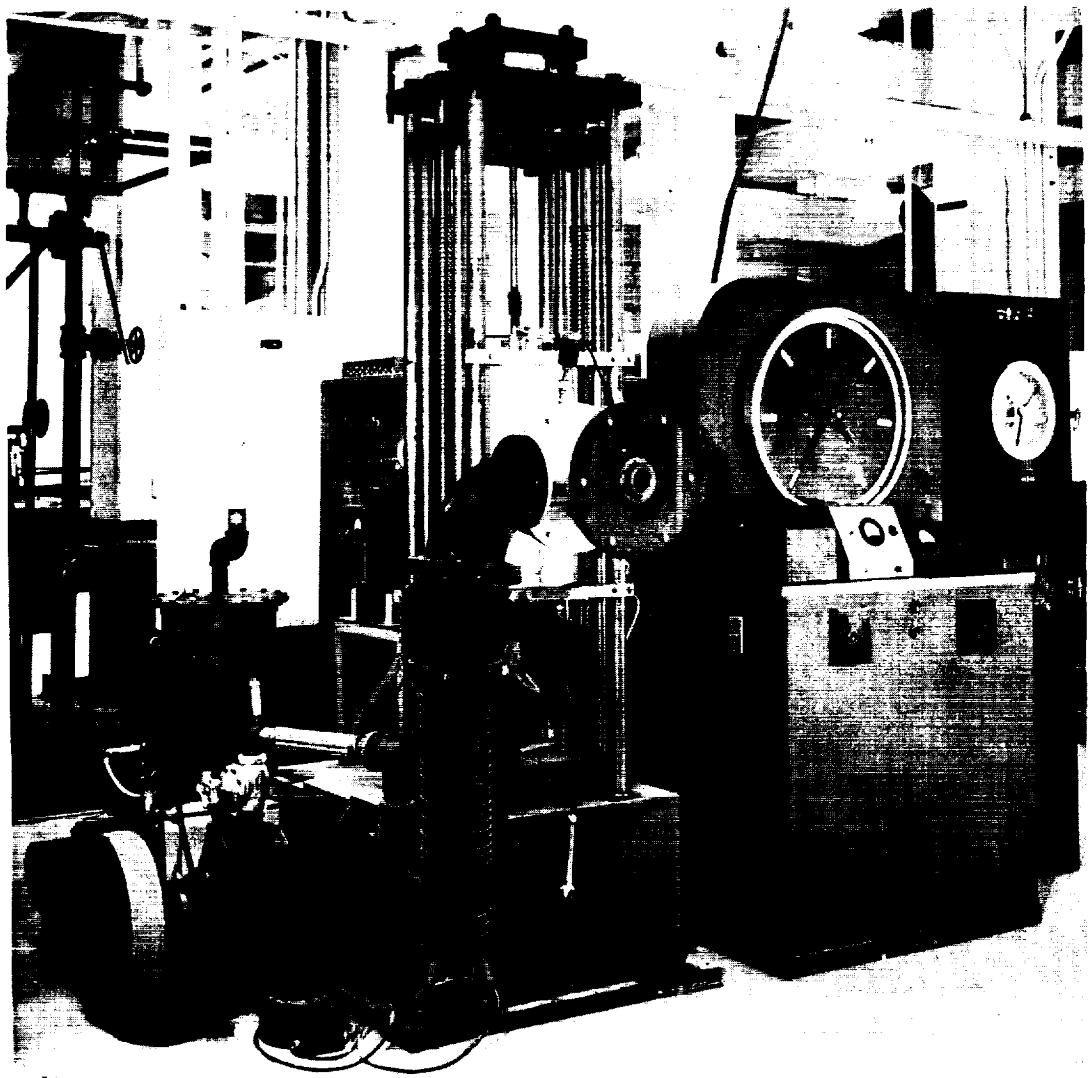


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Figure 2. - High-temperature tensil·: test equipment.

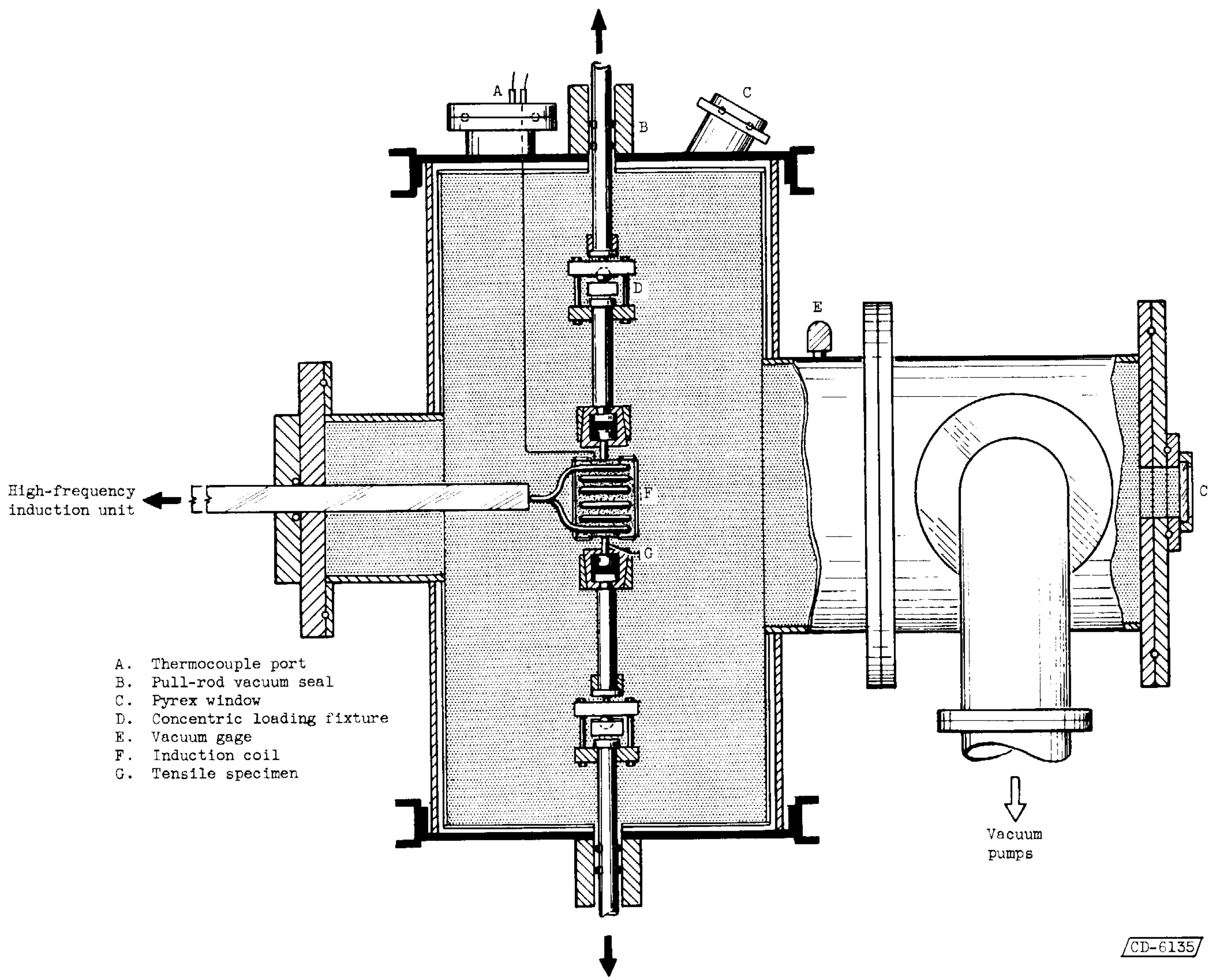
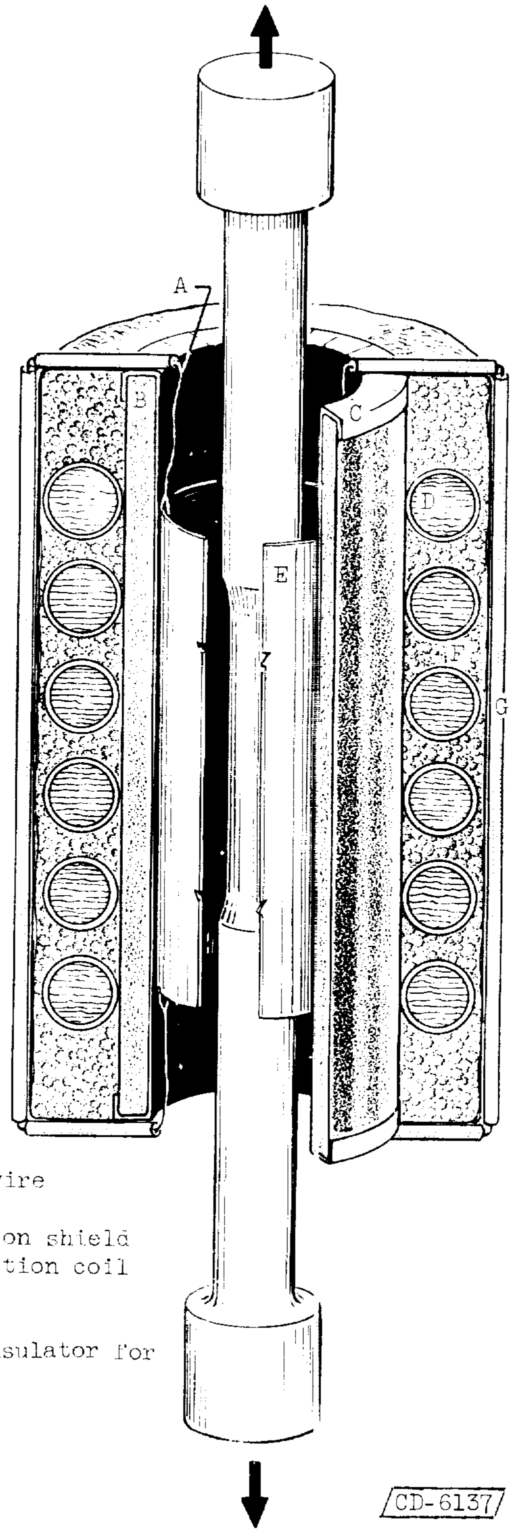


Figure 3. - High-temperature tensile test chamber.



A. Tantalum support wire
B. Alumina tube
C. Molybdenum radiation shield
D. Water-cooled induction coil
E. Tantalum susceptor
F. Alumina cement
G. Alumina tubing (insulator for support wires)

Figure 4. - Heater assembly.

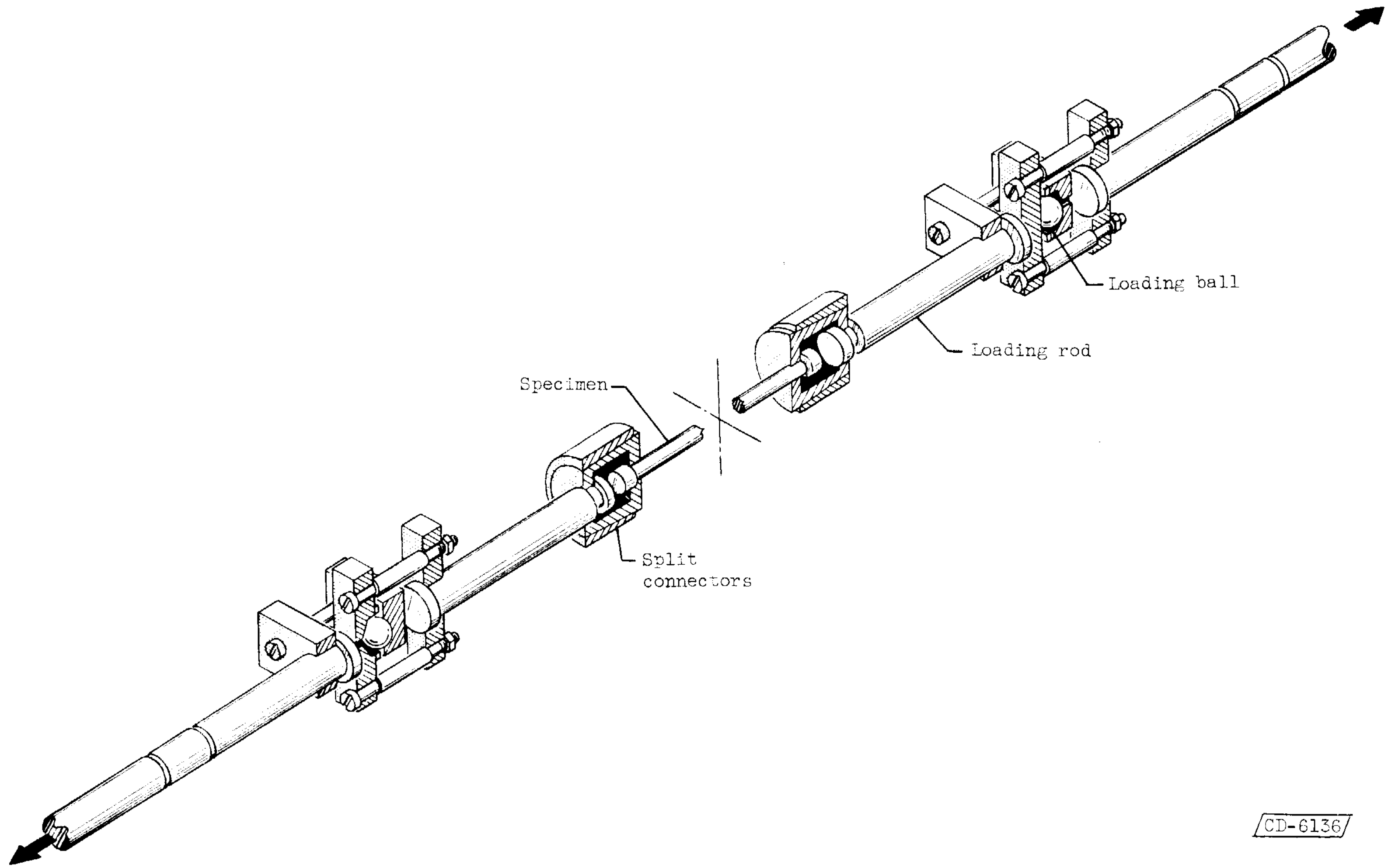
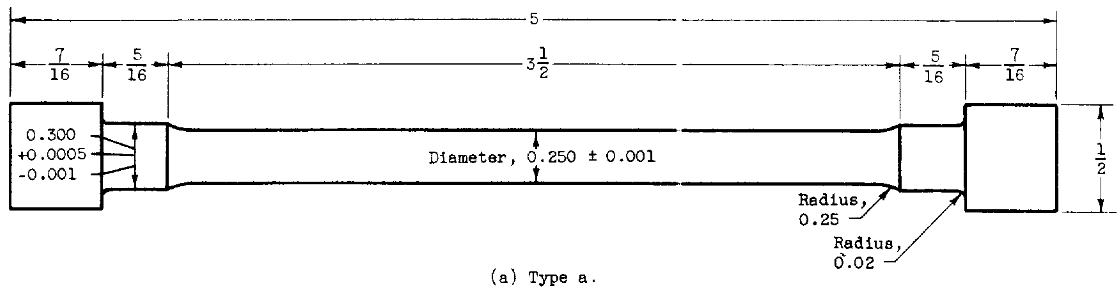
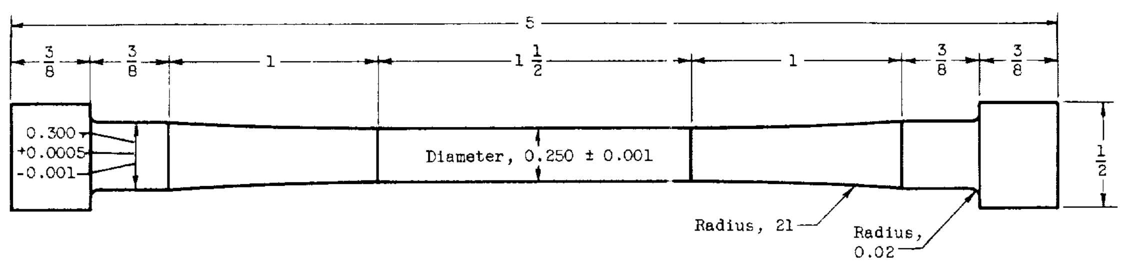


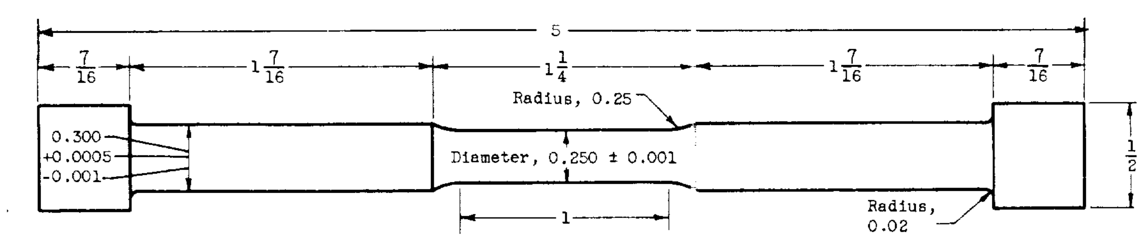
Figure 5. - Axial loading fixtures.



(a) Type a.



(b) Type b.



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(c) Type c. .

Figure 6. - Tensile test specimens. (All dimensions in inches.)

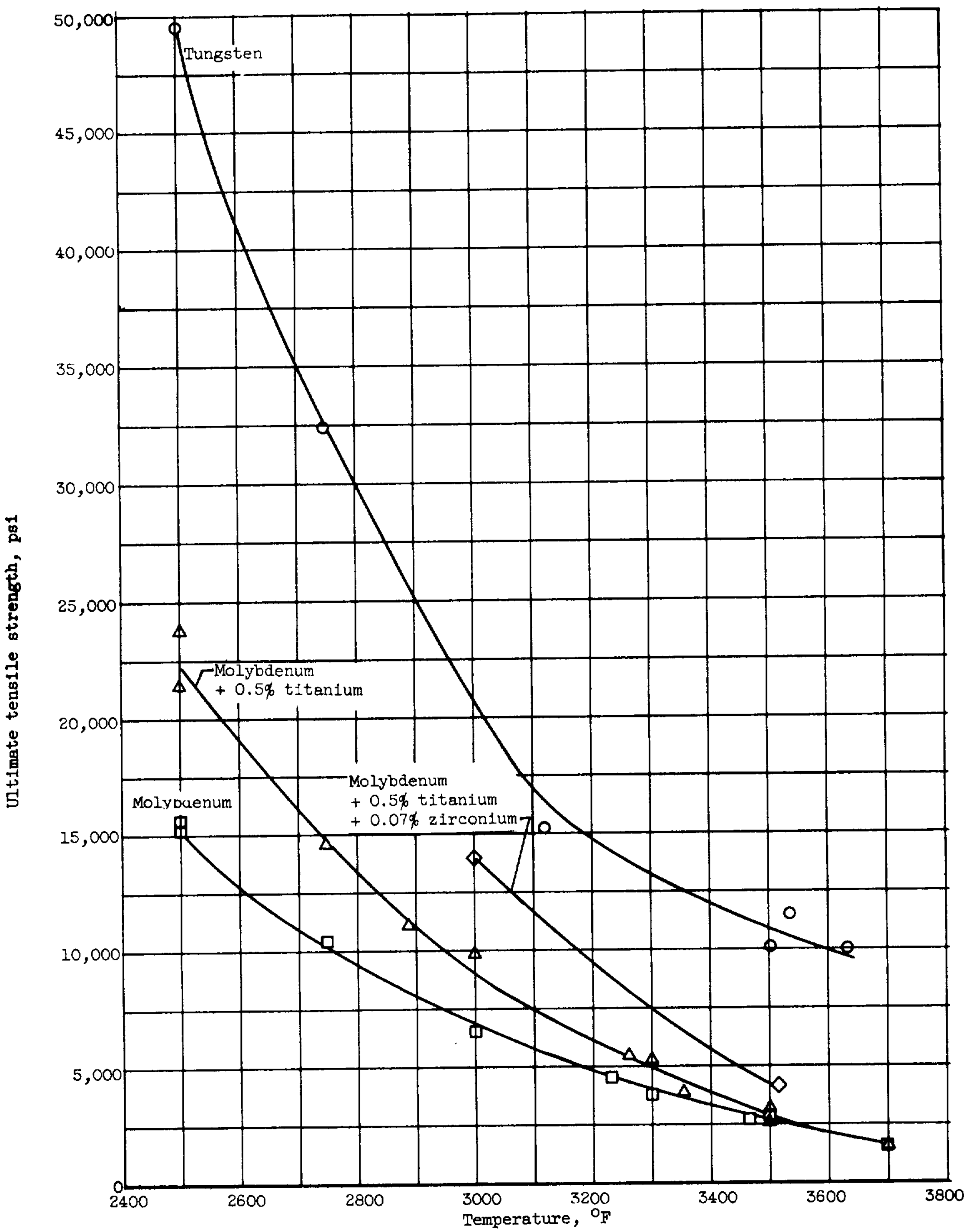
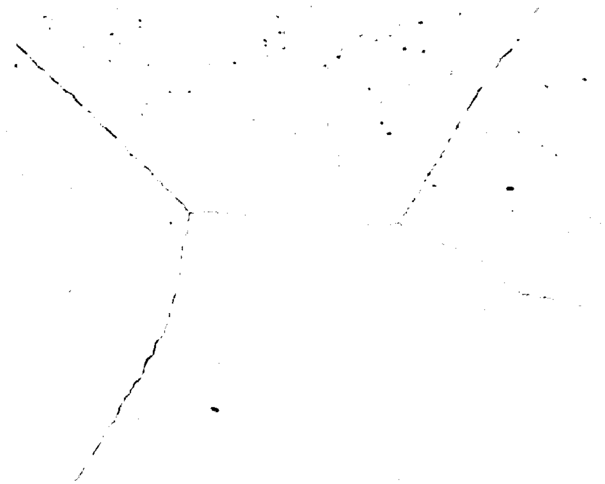


Figure 7. - Effect of temperature on short-time tensile strength of as-received tungsten, molybdenum, and molybdenum alloys.



(a) **Unalloyed molybdenum.** X250.

X250

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X1000

(b) Molybdenum plus 0.5 percent titanium.

Figure 8. - Microstructure of as-received molybdenum plus 0.5 percent titanium fractured at 3500° F.

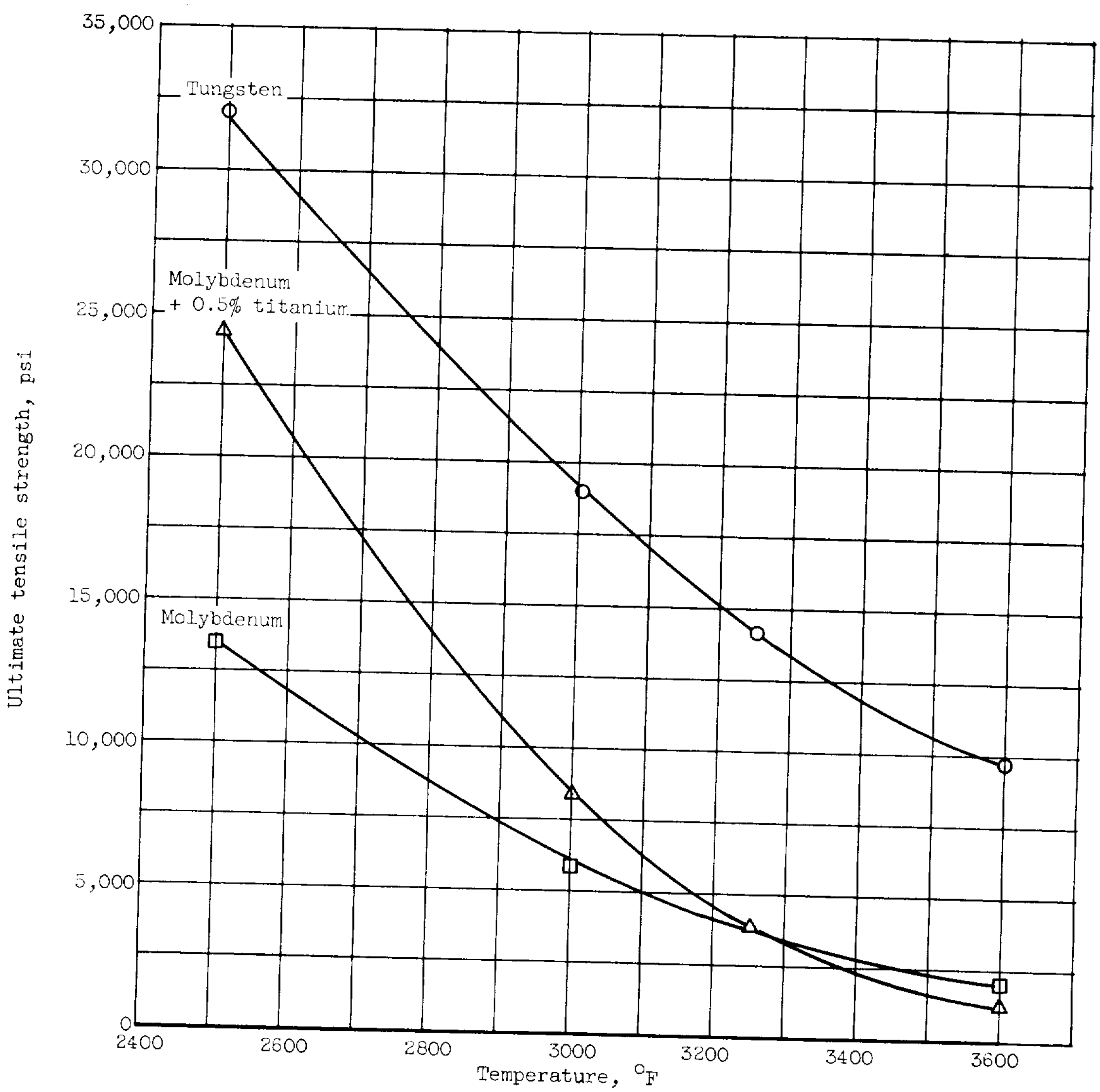
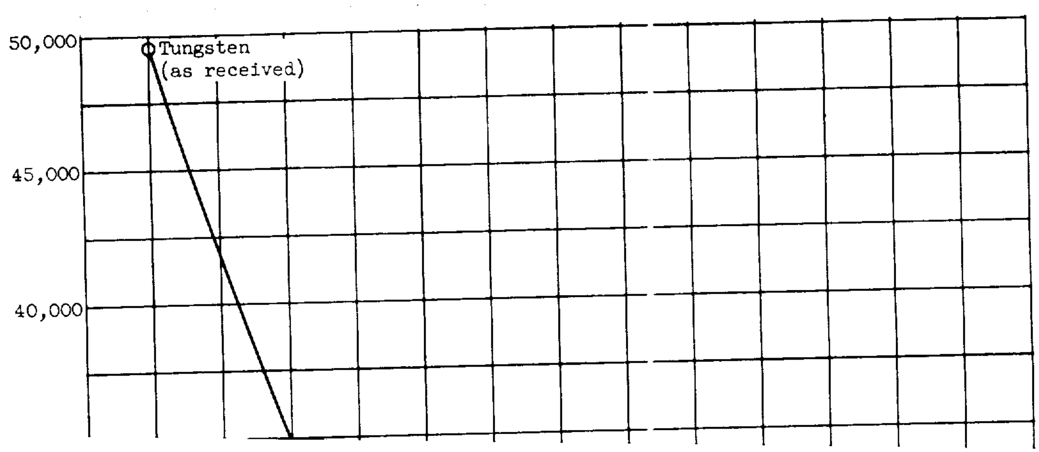
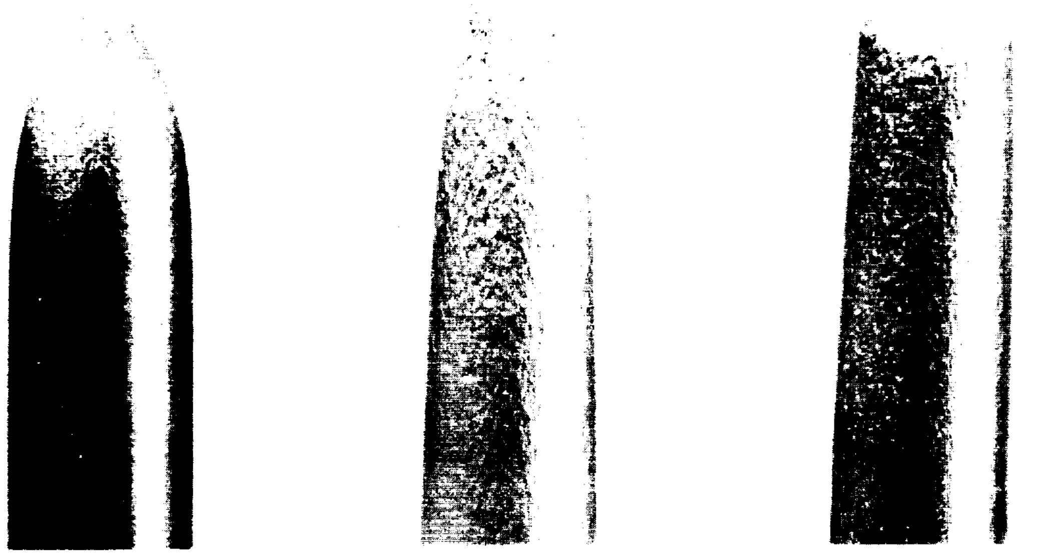


Figure 9. - Effect of temperature on short-time tensile strength of recrystallized tungsten, molybdenum, and molybdenum plus 0.5 percent titanium alloy.





C-48425

(a) 2500° F.

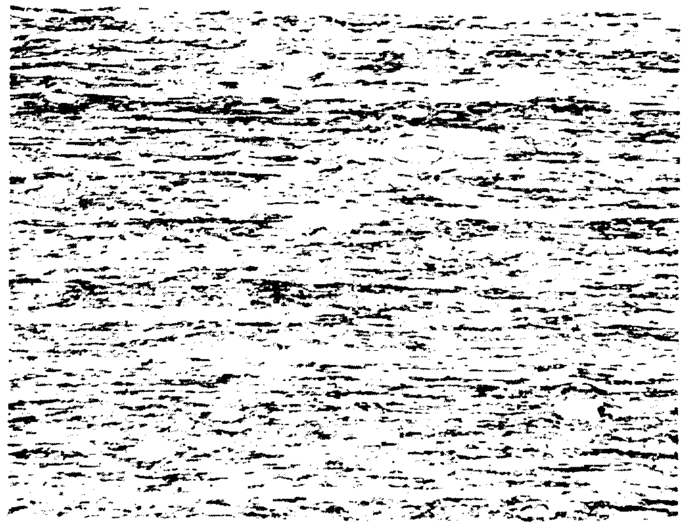
C-48426

(b) 3120° F.

C-48427

(c) 3530° F.

Figure 12. - Change of fracture type of as-swaged tungsten in tensile tests at high temperatures. X4



(a) As rolled.

(b) Fractured at 3230° F.

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(c) Fractured at 3460° F.

Figure 13. - Appearance of carbides in unalloyed molybdenum. X250.

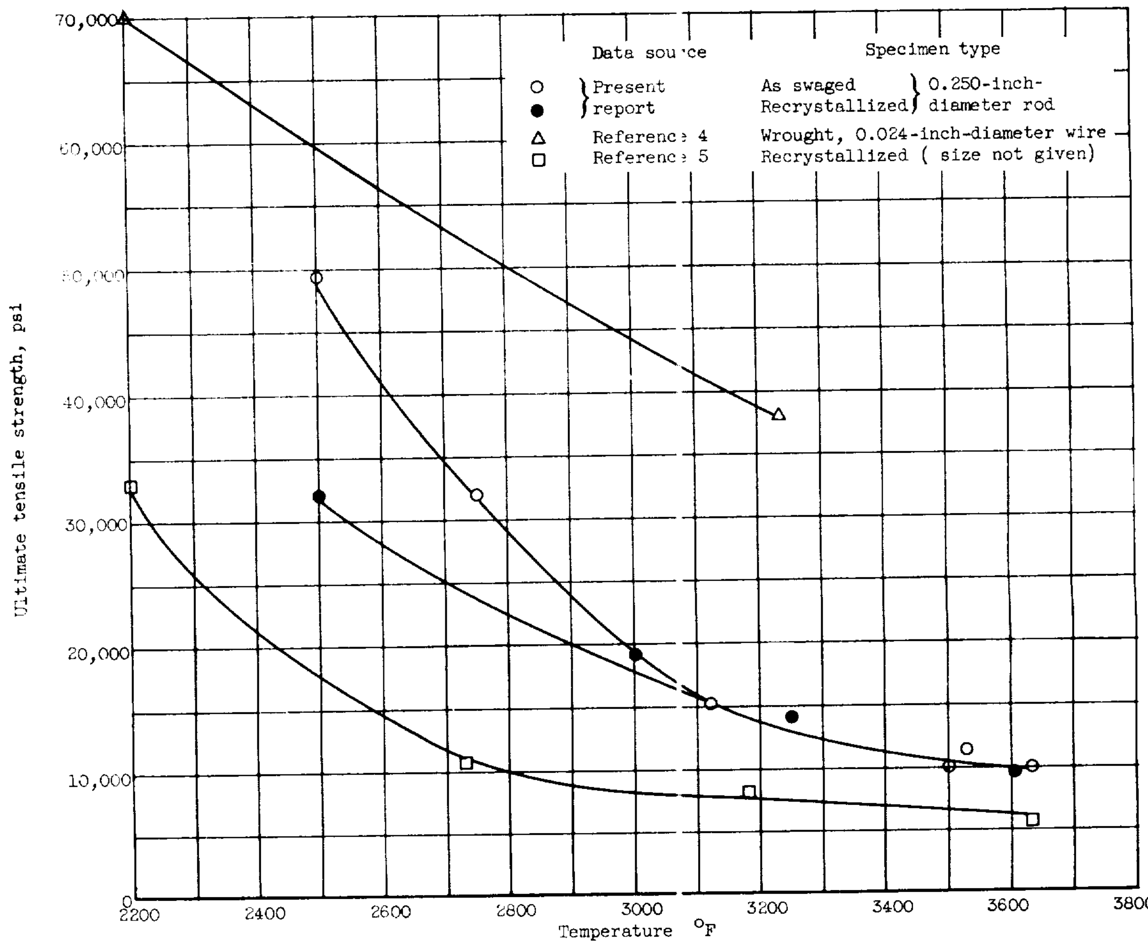

Figure 14. - Comparison of data for elevated-temperature tensile strength of tungsten.